Final Degree Project

Engineering in Industrial Technologies

Modelling of transmission systems for the integration of renewable generation

THESIS

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To Aarón, my life partner, for helping and supporting me in any situation, especially in the most difficult moments. Your optimism has helped me to always look forward.

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Summary

Society has nowadays a high electric energy demand, mainly due to technology development and the increase of needs that require this sort of power. Dispositives such as a microwave, a washing machine, a TV or our smartphones need, at some point in their use, connection to the electric grid at our homes. Therefore, it is vital to exploit renewable sources, which normally are located in remote places, in order to satisfy these needs, in an optimal way, considering all the related aspects, such as the economic and geographical.

Overhead lines in High Voltage Alternating Current (HVAC) are the conventional technology of power transmission, and have been widely studied, disposing of their own optimized mathematical model, for steady and transient states. However, there are other alternative technologies available for long distance transportation, such as Gas Insulated Lines or onshore and offshore cables. These options are worth a further study, due to economical, geographical and environmental issues, as well as new materials research, in order to improve the traditional bulk power transmission, whilst decreasing the harm to the environment.

Thus, the current thesis aims to establish a specific tool with the purpose of calculating the equivalent electric parameters of several transmission technologies. This tools, which takes the form of Matlab programs, is adapted to an already existing software package afterwards, in order to analyse power flow problems. These programs calculate the equivalent parameters of the system (such as the resistance, capacity and inductance, known as RLC), in order to be included in the Matpower system, where a further study is possible thanks to the power flow analysis.

As shown in the body of this thesis, it is previously necessary to study the background of each technology (having each their own variations), to model them afterwards. A brief explanation of the method used in the power flow analysis is also shown in this thesis, as well as the introduction of the mentioned parameters.

In conclusion, this study intends to explain a simple, yet powerful and helpful designing and testing tool in the field of electric engineering, regarding these current power transmission technologies. These programs were written in a clear and concise manner, making the software available and easy to understand.

Preface

Project origins and motivation

The project *Modelling of transmission systems for the integration of renewable energy* arose due to the current need of easily model and study the power transmission technologies available to this date. As renewable energies are gaining ground in this field, all the softwares related to the study and design of transmission systems ought to consider this progress, introducing the newest technologies.

Hence, the main objective of this thesis is not only to find an accurate and practical mathematical model easy to work with, but also compute power flow problems, thus giving all the important characteristics of the system, allowing the engineer to optimise it before the project is practically implemented. This modelling and testing of the transmission system will be achieved thanks to the potential of Matlab software, with functions specifically written for each technology case.

Thus, despite having the modelling of transmission systems been widely studied, the main motivation of this project was to design these programs in order to be implemented into Matpower afterwards, a powerful tool that calculates voltages, losses and generated and consumed power at the system. The reader is then encouraged to consult the related bibliography, in order to comprehend the behaviour of each transmission technology more in depth, although this topic is covered in the body of this thesis.

TABLE OF CONTENTS

1. Introduction

An Electric Power System is essential for the comfort and progress of our society. These systems allow us to supply electric energy with enough quality in order to accomplish the vast majority of our modern necessities, such as driving a motor, enlightening a street, watching TV or making a factory work.

The initial point of an Electric Power System is the generation source, which converts mechanical energy (except for the photovoltaic stations) to electric. This energy is later transferred from long distances to substations (mainly consisting in transformers), thanks to transmission lines. This electric energy is finally delivered to all the different intake points through distribution grids.

Thus, the main purpose of this project is, on one hand, to introduce an already existing mathematical model of power transmission systems (specially new transmission technologies) into several Matlab functions, obtaining the RLC parameters of the line, taking into consideration possible effects in the distribution line, which are, in most of the situations, harmful to the network. Some of these effects are the skin effect and spiral (or braided) effect, amongst others, which will be briefly explained in the following chapters. On the other hand, this thesis aims to include these parameters into a power flow analysis, in order to check the mathematical model and elaborate a complete study of the transmission lines.

With the purpose of understanding the core of the project, it is previously necessary to introduce the structure of electric power systems, as well as its elements (such as stations, transformers, materials, geometry of the wires and cables, etc) and available transmission technologies, amongst others.

In further sections, an exhaustive study of the equations, parameters and final model of each system, is shown to the reader. The considered transmission technologies are the traditional overhead lines, as well as cables and gas insulated lines. Finally, these elements, obtained thanks to the specification of the geometry and materials of the system, are introduced in a power flow analysis (using the Matpower library), in order to verify the efficiency, functioning and adaptability of the mathematical model.

2. Structure of Electric Power Systems

As mentioned before, electric power systems are mainly formed by electric power generation plants, which converts mechanical energy (in almost all cases) to electric, transmission and distribution lines that cover long and medium distances in order to deliver this energy to the uptake points, and substations that allow to connect lines and change voltage levels, amongst other functions. This basic structure can be appreciated in Figure 1. The main elements of an electric power system are briefly commented in their respective chapters.

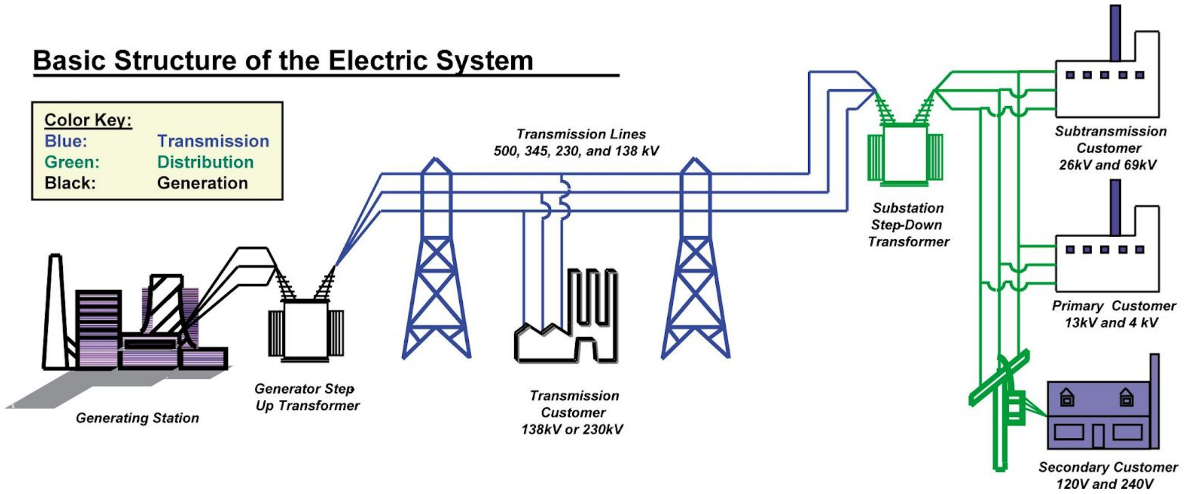

Figure 1: Schematic structure of the electric system.

2.1. Generation stations

Electric energy is obtained from the conversion of other types of primary power sources. The process in order to achieve this, normally occurs in big generation stations. There are a lot of different generation mechanisms. The most popular are the thermoelectric (such as solar, nuclear or combustion), hydroelectric, eolic and photovoltaic sources. The general procedure of energy conversion in every main station type is explained below[1]:

- **Thermoelectric stations**. This type of power generating facilities contemplates concentrated solar, nuclear and coal conversion mechanisms. All of them exploit the produced heat (either from solar radiation, from fuel or from nuclear fission) in order to obtain steam, which will move a turbine. The kinetic energy of this dispositive is transformed into electric energy thanks to the flux variation, which induces voltage in the generation machine, following

[1] More information can be obtained by checking the document shown in the bibliography as number [1].

Faraday's law. Finally, a transformer is needed, in order to step up the produced voltage to the further transmission lines.

- **Hydroelectric stations**. Power generation at these stations can be understood as the exploitation of the potential energy from the falling waters (usually from a swamp), which move a series of turbines (in case the station is big enough). It is thanks to this kinetic energy that the generator starts rotating, following the same principle as the mentioned before. At the end of the station there is also a transformer, as seen in Figure 1.

- **Wind farms**. These power generation facilities follow a similar concept as in hydroelectric stations. Although there are many types of wind turbines, the principle is the same in all of them, being those with horizontal axis the most common ones. The kinetic energy from the wind causes the movement of the turbine blades, connected to a generator, with the same functions as mentioned before. Almost every wind station is *onshore*[2], but the *offshore* facilities are being highly considered nowadays, due to better efficiency as the traditional ones.

Figure 2: Wind Tree Project (from NewWind french company)[3].

- **Photovoltaic stations**. Thanks to the photoelectric principle, each photocell of a solar panel, mainly made of Silicon, converts the electromagnetic radiation from the sun to electric energy, due to the electron jump from the cathode to the anode. This radiation must have a threshold frequency in order to pull out an electron. The produced electricity is of direct current type. Thus, an inversor is required before this energy is transferred to the grid.

[2] I.e. installed on the land. On the contrary, *offshore* wind stations are located at the ocean.
[3] Related news can be seen at:
http://www.newsweek.com/new-tree-shaped-wind-turbine-be-installed-streets-paris-296591

2.2. Substations and transformers

Substations and transformers are essential in an Electric Power System. In order to improve the transmission and delivering of electricity (decreasing the Joule losses and allowing smaller cable sections), some voltage changes are necessary during its transportation. Not only this, but also are they vital elements due to the required safety in this type of current, that is to say AC (which tends to directly attract the person that touches it), and because of the high levels of voltage involved. Other security mechanism is meshing the network (thanks, indeed, to substations), increasing its maneuverability in case of a possible failure.

As previously mentioned, this sort of facilities are located at the end of the generating stations (in order to increase voltage), and previous to the distribution lines, where LV is required. Thus, different types of substations are described below:

- **Transformation stations**. As mentioned before, they increase or decrease the voltage level, depending on the main objective at the studied location (transportation with low losses, or distribution to homes and factories). Is in these first type of stations that we find an essential element in electricity, more specifically in the alternating current world: the transformer.

- **Distribution or maneuvering stations**. This sort of facilities interconnect lines with each other, in order to have a good distribution of electric power. Thus, they allow the meshed network formation, increasing the reliability of the system.

On the other hand, **transformers** can be located at both types of substations, allowing the variation of the characteristics of an alternating electric system (receiving power from a primary current, and delivering to a secondary one), such as voltage and current modules.

A transformer is basically constituted of a ferromagnetic core, and two or more coils, magnetically connected. Surrounding this set, an oil tank can be found, as these elements need a way of heat dissipation, as well as an expansion reservoir, in order to counterrest the transformer volume variations.

The basic principle of a transformer is the transformation relation that follows, obtained from the apparent power conservation between the primary and secondary circuits:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} = r_t \qquad \textbf{(1)}$$

Where N_1 and N_2 are the number of whorls in each coil (primary and secondary). The basic parts of the transformer can be seen in Figure 3 as follows:

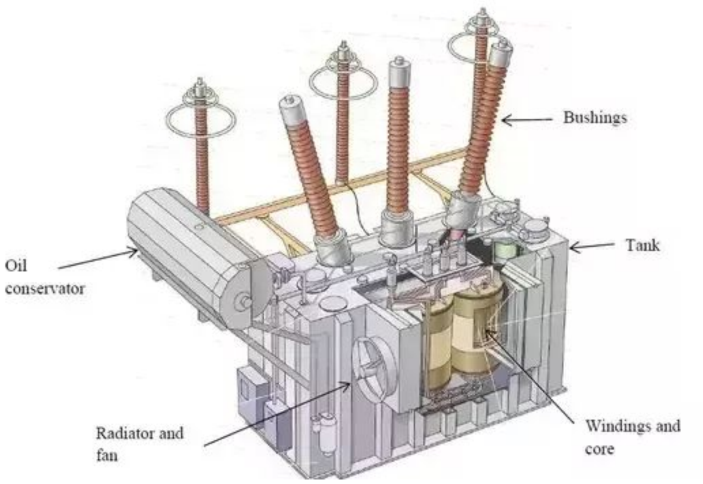

Figure 3: Basic parts of a transformer.

These elements are not defined in the Matlab programs, as they are not part of the mathematical model. However, they might be necessary afterwards, when defining the power flow problem, as it will be briefly explained in chapter 5.

The reader is remitted to references [2] and [3] in the bibliography to delve into substations and transformers.

2.3. Transmission and distribution lines

Electric Power Systems are also constituted of transmission and distribution lines, which should not be considered as equal elements. As transmission lines cover power transportation from very long distances at HV (from 66 kV to 220 kV or more[4]), distribution lines allow electricity to be delivered from medium or short distance substations at MV or LV (underneath 66 kV, where LV wires distribute 1 kV -effective value- electricity at maximum), to different bulk points. These two structures are briefly explained below:

- **Transmission lines**. These elements of the Electric Power Systems are vital to the transportation of the generated energy to every step-down substation. As they work at HVAC (High Voltage Alternating Current), they need a previous transformer in order to increase this voltage. The main purpose of this operation is to reduce losses from Joule effect at long distance operations, as current decreases.

- **Distribution lines**. These items of the electric grid need a previous step-down station, in order to decrease the electricity voltage, so it can be consumed. As can be observed in Figure 1, the main power consumers can be subtransmission, primary or secondary ones, with differences in their power demands.

[4] According to the spanish "Real Decreto 223/2008".

It ought to be noted that transmission lines tend to be aerial, whilst underground networks are not as common as the first ones. Although they are more reliable at steady state conditions, their economical cost and tough installation makes it difficult to develop this sort of transmission technology, which will be further studied. However, these newer technologies are, in some situations, the only possible alternative in power transmission, such as in offshore transportation. Moreover, they tend to impact less the environment.

2.3.1. Types of transmission technologies

It is known that power transmission has traditionally been by overhead lines. However, new technologies are making their way this past years, due to economical, environmental or geographical reasons. Thus, the present study aims to study and model these not-so-typical systems (i.e. finding its parameters and introducing them in a power flow analysis).

Table 1 briefly briefly describes the current HVAC and HVDC transmission systems considered in this study, and their relevant characteristics[5], as follows:

<table>
<tr><td rowspan="3">Overhead lines (HVAC and HVDC)</td><td colspan="2">Conventional power transmission system, with ACSR (Aluminium Conductor Steel Reinforced) as typical conductor. Technology not restricted by the landscape, cheap, easy to repair, with low chances of electrocution. However, sag formation, visual pollution, obstacle for aircraft and wildlife may be considered, as well as its affection regarding weather conditions.</td></tr>
<tr><td colspan="2">Current situation. New HTC[6] are being considered:
○ ACSS (Aluminium Conductor Steel Supported)
○ ACCC (Aluminium Conductor Composite Core)
○ ACCR (Aluminium Conductor Composite Reinforced)</td></tr>
<tr><td colspan="2">Examples.
○ 260 km, 400 kV France - Italy line.
○ 80 km, 220 kV Belgium - France line.
○ 940 km, 500 kV HVDC Three Gorges - Changzhou line (China).</td></tr>
<tr><td>Cables (HVAC and HVDC)</td><td>Offshore cables</td><td>Mainly HVAC power transmission system, with insulated copper cables (three single-core systems or a single three-core cable). Maximum voltage of 550 kV. Depth of several hundred meters.
HVDC technology considers two main conductors:
MI and SCFF[7] cables. Voltages up to ±600 kV. Mainly long term subsea applications. These systems bear polarity reversal.
Extruded XLPE cables. Voltages up to ±320 kV, not bearing polarity</td></tr>
</table>

[5] Information retrieved from reference [4] of the bibliography.
[6] High Temperature Conductors, which allow sag to be smaller, in addition to achieve a better capacity.
[7] Mass Impregnated (MI, insulated with special paper and a high viscosity compound) and Self-Contained Fluid-Filled.

		reversal. Subsea applications.
		Current situation. XLPE cables are being considered (with desirable voltage of 550 kV). Burial depth could increase to 2500m. Premature failing causes to be studied and analysed in the further years[8].
		Example. ○ 250 kV HVDC submarine cable system between the Balearic Islands and the Iberian Peninsula (Spain). 237 km long[9].
	Onshore cables	Underground power transmission system, with XLPE cables (chapter 4.4.2). Maximum voltage of 550 kV. With reduced visual impact, small Electric and Magnetic Field values (*Figure 4*) and losses, unaffected by weather conditions. However, higher installation cost and maintenance and long outage times after damage ought to be considered.
		Current situation. Partially underground solutions are being considered with 400 kV, 1,8 kA and copper cables with 2500 mm^2. Transient behaviour, compensation of reactive power and long outage times after failure should be studied.
		Example. ○ TenneT 380 kV AC Randstadt project, The Netherlands (85 km, 20 km underground, XLPE cable).
Gas Insulated Lines (GIL)	HVAC and HVDC transmission systems, with gas mixture of 80% N_2 and 20% SF_6. With voltages from 245 to 550 kV and a high EMC (electromagnetic compatibility). No fire hazard, with low losses and maintenance. Easy to detect possible failures. Central aluminum conductor with a section of up to 5,300 mm².	
	Current situation. New gas mixtures being considered (environmentally harmless and reciclable).	
	Examples. ○ 420 kV GIL system at Elstree, London, (Great Britain). ○ 245 kV GIL system at Cairo North, (Egypt).	

Table 1: Brief description of the available transmission technologies.

In further chapters, each transmission system will be studied and modeled, in order to include its parameters into a power flow analysis.

[8] More information can be found in Annex 1: Analysis of Offshore Cable Reliability.
[9] Red Eléctrica de España (2011). *Interconexión Península - Baleares*. Retrieved from http://www.ree.es/es/actividades/proyectos-singulares/interconexion-peninsula-baleares#

2.4. Transmission materials and geometry

A brief introduction in wire types and materials is needed in order to properly elaborate and understand a mathematical model of transmission systems, as they totally influence calculation procedures, results and parameters.

2.4.1. Materials in transmission lines

When modelling a transmission line, the study of the different materials available in the market is vital to the successful fulfillment of its materialisation. Not only conductor materials are necessary in transmission lines, but also insulating and coating elements, in order to protect the cables from the environment, as well as not allowing the electric connection between phases.

The current available materials and their characteristics are further explained in the following sections. The reader can find more information regarding this topic in the references [5], [6] and [7] from the bibliography.

2.4.1.1. Conductor materials

The most commonly used conductor materials in transmission lines are tough copper and aluminium. This last one, due to its acceptable conductivity and low density, is used in transmission lines with long distances between electric posts. This material's major disadvantage is its poor ultimate tensile strength, as well as a worse conductivity than copper. In order to increase the wire mechanical resistance (especially to traction forces), aluminium cables are reinforced with a steel soul, a strong material which can easily absorb these sort of forces.

Although aluminium conductance is lower than in copper, it can be seen in Table 2[10] that it results, in general, in a cheaper material. This is the main reason why most of the HV lines have aluminium cables.

It ought to be said that variations in the different material properties are due to every aluminium, copper and steel alloys (with different impurities and percentages).

Material properties are of vital importance in the design and modeling of a transmission line, because of their direct implications in all the computation procedures, for example at the inclusion of corrective factors, which take into consideration adverse phenomenons, such as the corona discharge or the braided effect, amongst others. These and other aspects will be further explained.

[10] Values retrieved from reference number [8] of the bibliography.

	Aluminium[11]	Copper	Low alloy steels	Lead
Electric conductivity [S/m · 10^6]	36,59	57,97	9,71	4,81
Resistivity[12] [Ω·mm^2/m]	0,026	0,018	0,035	0,207
Density [g/cm^3]	2,7	8,9	7,8	2,7
Magnetic relative permeability	1,000023	0,99999	≃ 1,075	0,999983
Ultimate tensile strength [MPa]	90 - 572	220 - 1310	380 - 1760	12
Price [$/kg][13]	6,10 - 11,65	3,20 - 47	0,50 - 3,30	
Temperature coefficient [1/ºC]	0,00403	0,00381	≃ 0,0039[14]	0,0043

Table 2: Conductor materials properties.

Moreover, material properties (resistivity in a special way) allow engineers to decide which to use, in order to minimise power losses, as well as acquiring a competent pricing in the realization of a transmission line. Environmental aspects of each material should also be considered, such as HCl (hydrochloric acid) fumes formation when a cables is on fire.

2.4.1.2. Insulating and coating materials

Aerial HVAC cables are usually bare, due to the dielectric properties of the air (when it is not ionized). However, in other type of lines, such as HVAC underground and sea transmissions, dielectric materials are highly considered and recommended whilst coating and insulating the cables.

There is an important difference in the purpose of insulating and coating elements. On one hand, insulating materials ensure there is no electric connection between the two current carrying components of the cable (the conductor and the metallic screen). Some typical materials are XLPE (cross-linked polyethylene, substitute for FF and GF cables) and EPR (ethylene-propylene rubber). It can also be oil impregnated paper (fluid-filled or

[11] In the case of Aluminium Conductor Steel Reinforced: resistivity of 0,035 (same units) and relative permeability of 1,075 (most relevant characteristics in this study).
[12] At a temperature of 20-25 ºC.
[13] Depending on its form, application and constitutive impurities.
[14] Approximative value corresponding to an aluminium-steel alloy.

mass-impregnated). Whilst the first one has less dielectric losses than EPR, it is more sensitive to insulation impurities. Another interesting insulating material is the SF_6 gas (sulfur hexafluoride), which highly decreases the magnetic flux density surrounding the line, as can be appreciated in Figure 4. This insulating system is mainly used in Gas Insulated Lines (GIL)[15].

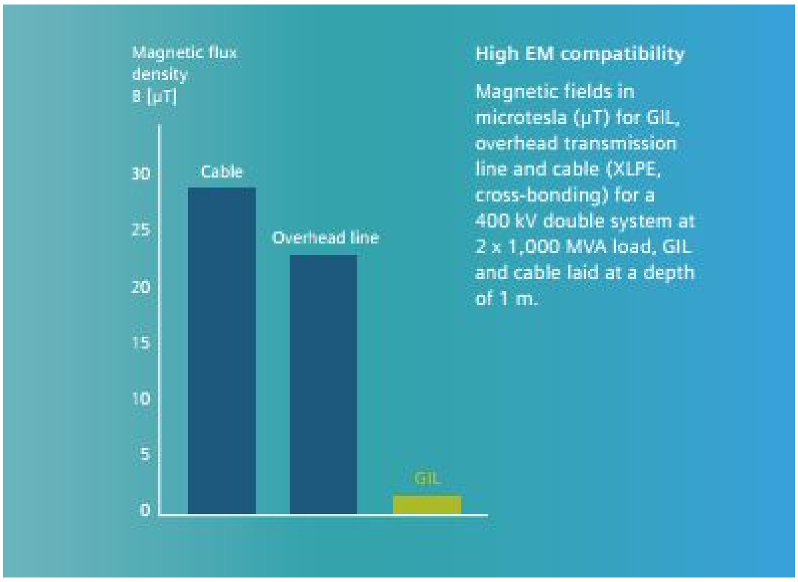

Figure 4: Comparison of magnetic fields for different HV transmission systems.

On the other hand, coating materials increase the wire resistance to environmental conditions, thus enlarging the line's life. As previously mentioned, aerial cables do not usually have this element in their structure, whereas they are vital in underground and sea transmission lines, where the surrounding materials can damage the cables (due to corrosion or oxidation). Some typical materials are LLDPE (linear low-density polyethylene), XLPE, HDPE (high density polyethylene) and PVC (polyvinyl chloride), amongst others[16].

It is necessary to mention that coating elements also protect the environment from possible fires, especially in cables near trees.

Some considerations regarding the geometry of the wires in the technologies studied in this paper are further explained.

2.4.2. Geometry of the wires

Another important aspect while modelling transmission lines is the disposition, thickness and number of layers of the different type of materials (explained in the previous section), amongst others.

[15] More technical information about this technology can be found in references number [9] and [10] of the bibliography.
[16] Materials found in *General Cable* and *Eland Cables* websites.

The study of the different options regarding the geometry of the cables should consider the efficiency in the electric transmission, as well as economical aspects and mechanical resistance to traction of the line. Thus, the geometry of the cables and the materials used in its materialization are closely related.

In the following sections, the distribution of the layers in the wires are explained for each transmission technology.

2.4.2.1. Geometry of the wires in overhead lines

In order to elaborate an accurate study of overhead lines, it is necessary to explain how the different layers are distributed inside the wires, and from which materials are they constituted. Considering the different options regarding the geometry and the possible materials of an overhead line allows the designer to optimize the power transmission.

Figure 5 shows the typical aerial wire for power transmission. It can be noted that this sort of cables tend to lack from coating and insulating elements (with the exception of those ones near trees). This type of wires is usually constituted by different number of aluminium (or copper) layers, braided-form distributed. Thus, few conductor materials are considered in the case of aerial wires: copper and aluminium are the main ones. Despite having copper better electric properties, aluminium with steel core shall be considered in order not to have mechanical failures due to environmental conditions, fatigue or sag formation, amongst others, as well as being cheaper than copper.

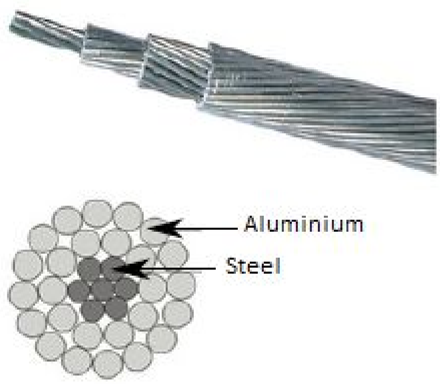

Figure 5: Geometrical structure of bared and reinforced wires.

It shall be noted that braided and skin effects should also be taken into consideration while making a mathematical model of the transmission line, as the transmission systems in this project are all HVAC in conditions.

2.4.2.2. Geometry of the onshore and offshore cables

The cable technology is normally defined by having its wires a considerable amount of layers and a complex structure, compared to overhead lines. Thus, taking into consideration the distribution of these different layers and the material with which they are designed is vital for its optimization (i.e. reduction of power losses and manufacturing costs). Figure 6 shows the typical wire structure for a single-core (SC) self-contained cable[17]:

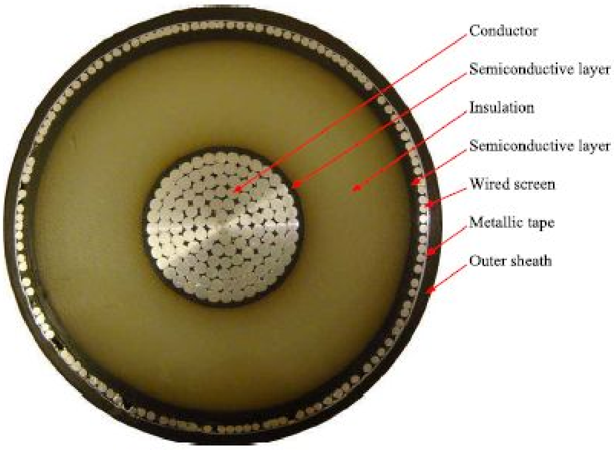

Figure 6: XLPE onshore single-core cable.

The main elements of an onshore single-core cable are explained below:

- **Core conductor**. It is formed by small wires, often disposed in a parallel distribution. Such wire disposal reduces the skin effect, allowing current density to flow closer to the cable core, far from the surface. The common materials used in conducting the electricity are lead, corrugated aluminum or copper.

- **Semi Conductive layer**. Its function is to reduce electric stress in the insulation layer, avoiding also the formation of voids, due to cable bendings during the power transmission.

- **XLPE or EPR insulation. Outer sheath**. The function of these layers has been explained at chapter 2.4.1.2. The insulation can also be achieved thanks to air or another dielectric fluid.

- **Metallic screen**. This layer is formed by the wired screen and the metallic tape, having a common purpose: to be an electrostatic screen, as well as a path for the charging current. It is also a safety mechanism in case there is a failure in the transmission cable, as it directs the short-circuit current to earth. This layer allows a three-phased system to be balanced, as it redirects the current flow.

[17] Image and information retrieved from reference [11] of the bibliography.

In case of having an offshore cable, it is mandatory to include a conducting armour, in order to increase the mechanical properties of the structure, surrounded by an insulating layer, which can be constituted by concrete, cast iron or plastics (in increasing amount), and ought to be considered whilst modelling offshore cables. In this thesis, only XLPE is considered (although the Matlab code can be modified accordingly, in order to study other materials).

2.4.2.3. Geometry of the cables in Gas Insulated Lines

As studied in the previous cases, the distribution of the different layers and the design materials used in this sort of technology are vital for the understanding and optimization of the line, in terms of reducing the power losses and manufacturing costs. Therefore, this section aims to show the current options for the distribution of the different forming materials of the Gas Insulated Lines (GIL).

The typical structure of GIL, which can be seen in Figure 7, usually has different layers of materials, similar to the cable case. The main difference between these technologies is the used insulating material, which is a gas in these systems. Each layer is briefly explained below.

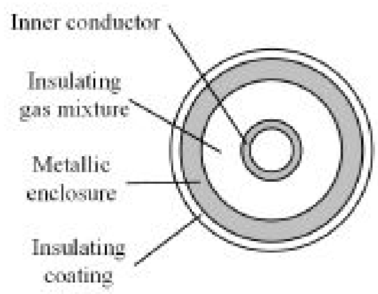

Figure 7: Geometrical structure of the gas-insulated line (GIL).

On one hand, at the center lies the conductor (which can be hollow or solid), usually made of an aluminium alloy of high electric conductivity. The other conductor layer, the enclosure, is formed by a sturdy aluminum tube, which provides a solid mechanical and electrotechnical containment for the system.

On the other hand, the insulating layer in this sort of transmission technology is formed by fluid materials, more specifically gas, as mentioned before. Although some new materials are currently being considered and studied, the current gas used to this purpose is a mixture of nitrogen (80 %) with a small percentage of SF_6 (20 %). Other insulating elements can be found in the centre of the cable, which also provide traction resistance to the system.

Finally, the coating layer, which provides protection to the wires regarding the environmental conditions (temperature and humidity of the soil, amongst others) which can cause the corrosion of the conductor, is normally formed by polyethylene. This coating layer is only necessary when the gas-insulated line ought to be directly buried in the ground, and shall be ignored in the mathematical study of this technology.

3. Electric parameters in transmission technologies

In this chapter, the different equations used in the modelling of each transmission technology will be presented. These expressions depend on the geometry of the system, as well as on the distribution and materials of the different conductor and insulating layers. Most of the equations and hypothesis shown in this chapter are retrieved from reference number [12], where more information about this topic can be found.

Thus, several models shall be elaborated for each transmission technology, taking into account these variations. These different options are translated therefore into having a program for each one, which will be further explained in chapter 4.

The electric constants introduced in the mathematical model, as well as this modelling structure will be explained in this section, for each transmission technology, being the possibilities:

- **Overhead lines**. In this project, the different considered options are whether the materials are copper, aluminium or ACSR, having this last one other equation, as it is modelled as a hollow conductor (see further sections), as well as being solid or stranded conductors. Thus, there are four different combinations, considering transposed systems in all of them.

- **Cables**. The considered alternatives are whether the cables are onshore/offshore (varying the number of layers) or pipe type, as well as the phases disposition (flat or trefoil formation).

- **Gas Insulated Lines (GIL)**. Despite being this technology similar (in geometry and behaviour) to any other cable (varying the insulating material), the only considered option is the onshore GIL, flat or trefoil disposition. The offshore case was not considered because gas insulated cables do not normally have an armour.

It shall be noted that the conductance term (being the remaining the resistance, inductance and capacitance) has not be taken into consideration, due to its small value in power flow studies (i.e. for low frequency values).

3.1. Electric parameters in HVAC Overhead Lines

In order to mathematically determine a transmission line, it is vital to study and understand its parameters, which elements are responsibles for every electric and magnetic behaviour or phenomenon, whether the produced losses are significant or not and how these elements interact between each other, amongst others.

It is necessary to remember that, while designing a transmission line, a balance between manufacturing costs and power losses (which are also economical costs) should be achieved. Therefore, different material properties (such as resistivity and magnetic permeability) and geometries (transversal area, conductors' distribution inside a cable, etc.) ought to be considered in order to achieve this desirable situation, as well as the distribution of all the conductors.

A HVAC transmission line has four primary constants that influence its functionality as part of a power system: resistance, inductance (both of them being longitudinal parameters), capacitance and conductance (being those lasting, crossed terms). These parameters are determined thanks to the geometry and distribution of the conductors, as will be seen afterwards. The general geometries of these transmission technologies is the one shown in further sections (Figure 11, 12 and 13).

Thus, the following general hypothesis are considered in the calculation of the electric parameters in overhead lines:

- Steady and stable state situation[18], achieved thanks to a meshed grid structure and all the other safety elements (such as lightning rods and arresters, insulators, etc).

- The distance between conductors is considered as constant, as well as between conductors and the ground. The diameter of each conductor is underestimated in the determination of these distances.

- All the conductors have cylindrical form in this study, as well as an homogeneous material distribution, having all of them the same dimensions.

- Only single circuits are studied, i.e. those with three conductors. The phases may be disposed in any desired arrangement, thank to the definition of the distances between them (see Figure 11).

- The system is assumed to be transposed (having each section the same length, $l_1 = l_2 = l_3 = \frac{l}{3}$, as it can be appreciated in Figure 8), as this measure is considered in almost all the lines. Only this case is studied in this project.

[18] Although energy demand, as well as voltage and current, are permanently changing, a steady state can be considered. The reader is encouraged to visit reference number [13] in order to be informed about the transient behaviour of transmission systems, topic not covered in this thesis.

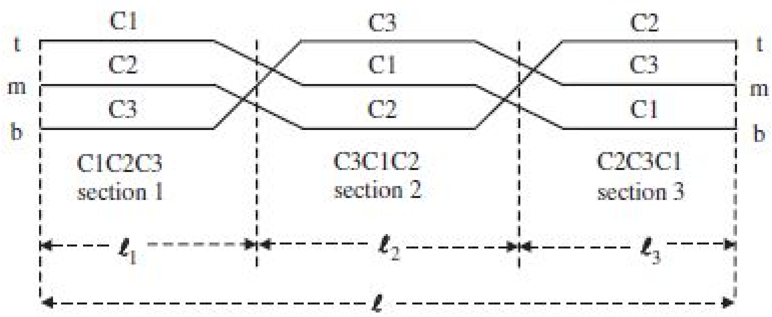

Figure 8: General case of phase transposition of a single-circuit three-phase line.

- All the electric parameters are equally distributed along the line, due to the small effect of the transmission towers and other objects in their determination.

- As a consequence of the previous premise, the electric parameters are considered as constants (for each combination of characteristics in the line), independently from the operation conditions.

- The conductance parameter is considered as negligible, due to the poor influence of the corona effect. Furthermore, this constant is usually not taken into account in power flow analysis.

- The soil is considered as the point at zero potential. Moreover, the influence of the ground cables to each phase is considered as negligible, as the lines are perfectly transposed. Thus, they are bonded to the top of the middle tower but insulated at the adjacent towers on either side (which means $I_{s_i} = 0$, being s_i the subscripts for earth wires). They are thus eliminated in the determination of the impedance and conductance matrices (Z_{pnz} and B_{pnz} respectively), as will be further appreciated.

It is necessary to clarify that, although all the important parameters in a transmission grid (i.e. resistance, inductance, capacity and conductance) are distributed, when an equivalent circuit is required, and thanks to the previous premises, these items must be considered as concentrated, as well as per unit length. Moreover, each equivalent circuit will be equal and independent between the three phases, as it can be appreciated in the PNZ[19] transformation (which will not be covered in this study, as this topic is covered in many books), simplifying the analysis of the transmission line.

3.1.1. The π-section nominal model

As it has been previously introduced, a steady state simulation of a transmission line is done thanks to the analysis of a simplified equivalent circuit, where the mentioned parameters (i.e. resistance, inductance, capacitance and conductance) appear. Thus, if we

[19] Meaning PNZ positive (P), negative (N) and zero-phase sequence phasors, which form a balanced set.

know the final values of voltage and delivered power, the initial voltage and current can be calculated. The result of these values may further determine the efficiency of the line, as well as its cost (including the one due to the quantity of the material and the related to power losses) and terms such as its initial power, amongst others.

The length of the transmission line determines the best equivalent circuit and model for the simulation, changing the mathematical expressions of the characteristic parameters in this model. However, only the model belonging to medium distance lines is considered in this study (those with a length from 50 to 250 km).

The voltages at the beginning and at the end of the line can be related thanks to the transmission matrix, in order to properly determine important values of the circuit such as the voltage drop. The equation system is the one shown below:

$$\begin{bmatrix} \underline{V}_{s,o} \\ \underline{I}_o \end{bmatrix} = \begin{bmatrix} \underline{A}_{11} & \underline{A}_{12} \\ \underline{A}_{21} & \underline{A}_{22} \end{bmatrix} \begin{bmatrix} \underline{V}_{s,f} \\ \underline{I}_f \end{bmatrix}$$

(2)

This sort of system allows studying the transmission line as a quadripole, being A_{ij} the coefficients of the transmission matrix, which vary with the length and mathematical model of the line. Connected to this quadripole, a power source can be found at the beginning, as well as a main uptake point at the end. Such disposition can be appreciated in Figure 9:

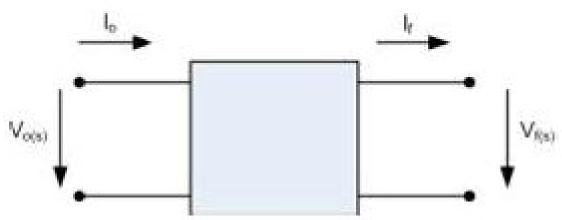

Figure 9: Transmission system seen as a quadrupole.

In HVAC medium-length lines, the most practical simplification is the π-section model, which is the one that follows (Figure 10):

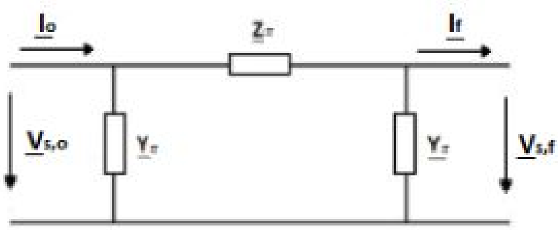

Figure 10: Equivalent π circuit mathematical model for medium length lines.

This model allows a great simplification of the terms in the transmission matrix (where the exact $A_{ij,}$ parameters include hyperbolic functions[20]), while losing few precision in the process. Thus, the transmission coefficients of a generic medium transmission line are the ones that follow:

$$\underline{A}_{11} = \underline{A}_{22} = 1 + \underline{Z}_{\pi}\underline{Y}_{\pi} \qquad \underline{A}_{12} = \underline{Z}_{\pi} \qquad \underline{A}_{21} = 2\underline{Y}_{\pi} + \underline{Y}_{\pi}^{2}\underline{Z}_{\pi}$$

(3)

Where:

$$\underline{Z}_{\pi} = \underline{Z}_{t} = (R + j\omega L)\cdot l \quad \textbf{(4)}$$

$$\underline{Y}_{\pi} = \frac{(G+jB)\cdot l}{2} \quad \textbf{(5)}$$

$$B = C\cdot\omega \quad \textbf{(6)}$$

Where B is the susceptance of the line, which measures the capability of the dispositive to store electric or magnetic energy (depending on being a capacitor, with a positive value, or a coil, with a negative value, respectively).

On the other hand, $\underline{Z}_{\pi}$ is the impedance in a π-section model (in Ω), thus of a single phase, $\underline{Y}_{\pi}$ is the admittance from this mathematical model (in S, or Ω^{-1}). These parameters are introduced in the π-section model in order to determine, thanks to the transmission matrix, the needed voltage and current at the beginning of the line. Moreover, they allow further studied with their introduction in a power flow analysis.

From the previous equations, it can be seen that modelling a line with this sort of equivalent circuit allows taking into consideration the existing ground influence in the capacitance of a phase (i.e. having capacitive currents between conductors or between these and the ground). Thus, this is the appropriate mathematical model to work with whilst studying overhead lines.

The determination of the electric constants introduced in the π-section model (and thus in the Matlab software) for the case of transposed overhead lines is explained in further sections. The case of single conductors in a phase will be studied, as well as stranded wires.

3.1.2. Unitary impedance

The resistance, as well as the inductance, will be studied in this section, as they are directly obtained from the impedance. It shall be noted that the parameters introduced in the model are those determined after the calculation of the PNZ impedance matrix, more specifically the term located at the first column and row (PPS term).

[20] See references number [14] and [15] from the bibliography for more information about the π-section model and transmission matrix.

All the equations refer to the case of having a single conductor in the phase, for materials such as aluminium and copper, as well as for the case of aluminium steel reinforced conductors (ACSR), which will be treated separately from the previous ones, as well as from the case of stranded conductors. Stranded conductors will be explained afterwards.

3.1.2.1. Series self impedance

The equations shown below assume infinitely long and horizontal conductors, with an homogeneous earth underneath (having a uniform resistivity and unitary relative permeability). Thus, the self impedance of the conductor *i* (i.e. one of the phases) term is the one that follows (in Ω/km):

$$Z_{ii} = [R_{i(c)} + jX_{i(c)}] + jX_{i(g)} + [R_{i(e)} + jX_{i(e)}] \quad \textbf{(7)}$$

Being the subscripts *c* those relative to the conductor (representing the internal terms), representing *g* a reactance contribution and *e* those related to the influence of the earth, as correction terms. As the skin effect is taken into account in this thesis, the exact first term (referring to subscript *c*) is as follows (for solid conductors):

$$Z_{i(c)} = \frac{\rho_c}{2\pi r_c}\cdot(\sqrt{2}\cdot\delta^{-1}\cdot e^{j\pi/4})\cdot\frac{I_o[(\sqrt{2}\delta^{-1}\cdot r_c)\cdot e^{j\pi/4}]}{I_1[(\sqrt{2}\delta^{-1}\cdot r_c)\cdot e^{j\pi/4}]} \quad \textbf{(8)}$$

Being:

- ρ_c: resistivity of the conductor in Ω·mm²/m.
- r_c: radius of the conductor, in mm.
- $\sqrt{2}\cdot\delta^{-1}\cdot e^{j\pi/4}$: complex propagation constant, with δ as the skin depth, which represents the depth of penetration of the skin effect, i.e. the surface affected by this phenomenon. The skin depth is calculated as follows (in m):

$$\delta = 503,292\cdot\sqrt{\frac{\rho_c}{f\cdot\mu_r}\cdot 10^6} \quad \textbf{(9)}$$

- I_i : modified Bessel functions of the first kind, of order *i*. More information about these functions can be found in Annex C and reference number [16] of the bibliography. While modelling this technology in Matlab, it shall be noted that there is an specific function regarding these equations.

It shall be noted that, for ACSR, this term is different due to the different geometry of the wire, being represented as a hollow conductor (as the effect of steel saturation is ignored), also in Ω/km:

$$Z_{i(c)} = \frac{\rho_c}{2\pi(r_o^2 - r_i^2)} \cdot \left(1 - \frac{r_i^2}{r_o^2}\right) \cdot (\sqrt{2} \cdot \delta^{-1} \cdot r_o) j \cdot \frac{D_1}{D_o} \quad \textbf{(10)}$$

$$D_1 = I_o[(\sqrt{2}\delta^{-1} \cdot r_o)\, e^{j\pi/4}] \cdot K_1[(\sqrt{2}\delta^{-1} \cdot r_i)\, e^{j\pi/4}] + I_1[(\sqrt{2}\delta^{-1} \cdot r_i)\, e^{j\pi/4}] \cdot K_o[(\sqrt{2}\delta^{-1} \cdot r_o)\, e^{j\pi/4}] \quad \textbf{(11)}$$

$$D_2 = I_1[(\sqrt{2}\delta^{-1} \cdot r_o)\, e^{j\pi/4}] \cdot K_1[(\sqrt{2}\delta^{-1} \cdot r_i)\, e^{j\pi/4}] - I_1[(\sqrt{2}\delta^{-1} \cdot r_i)\, e^{j\pi/4}] \cdot K_1[(\sqrt{2}\delta^{-1} \cdot r_o)\, e^{j\pi/4}] \quad \textbf{(12)}$$

Being r_i and r_o the inner and outer radius of the conductor, in m (although they are introduced in mm in the Matlab programs). K_i are the modified Bessel functions of the second kind, of order *i*.

On the other hand, the reactance contribution to the self impedance term is as follows (in Ω/km):

$$X_{i(g)} = 4 \cdot \pi \cdot 10^{-4} f \cdot log_e \left(\frac{2y_i}{r_i} \cdot 10^3\right) \quad \textbf{(13)}$$

Being r_i the inner radius of the conductor in the case of ACSR, or r_c otherwise. The term y_i represents the height of the conductor respect to the ground, in m.

Finally, the impedance term related to the influence of the earth can be calculated as follows, taking into account that, although being a series equation, it can be simplified thanks to the value of frequency (i.e. 50 or 60 Hz) in steady state simulations, which allows to consider the terms after the first one, as neglectable:

$$R_{i(e)} = \pi^2 10^{-4} f - \frac{f}{911{,}812 \cdot \frac{D_{erc}}{2y_i}} \quad \textbf{(14)}$$

$$X_{i(e)} = 4\pi 10^{-4} f \cdot log_e \left(\frac{D_{erc}}{2y_i}\right) + \frac{f}{911{,}812 \cdot \frac{D_{erc}}{2y_i}} \quad \textbf{(15)}$$

Where D_{erc} represents an equivalent conductor for the effect of earth return path, considering an earth relative permeability of unity, being as follows:

$$D_{erc} = 658{,}87 \cdot \sqrt{\frac{\rho_e}{f}} \quad \textbf{(16)}$$

Being ϱ_e the resistivity of the soil, in Ω·m. It shall be noted that its value is 20 Ω·m by default, but can be modified in the Matlab software, in order to simulate different earth conditions. A table with different values can be found in Annex E: Electrical properties of the ground. The reader is encouraged to visit this annex, as well as the references number [17] and [18] in search of more information regarding the electrical properties of the soil.

3.1.2.2. Mutual impedance

The mutual impedance between conductor *i* and *j* is calculated as follows, in Ω/km:

$$Z_{ij} = jX_{ij(g)} + [R_{ij(e)} + jX_{ij(e)}] \quad \textbf{(17)}$$

Being $X_{ij(g)}$ the reactance influence between phases, determined by the equation:

$$X_{ij(g)} = 4\pi \cdot 10^{-4} f \cdot log_e\left(\frac{D_{ij}}{d_{ij}}\right) \quad \textbf{(18)}$$

Where D_{ij} is the distance between conductor *i* and the image beneath the earth's surface of conductor *j* (in m), and d_{ij} is the distance between conductor *i* and conductor *j* (in m), as can be seen in Figure 11:

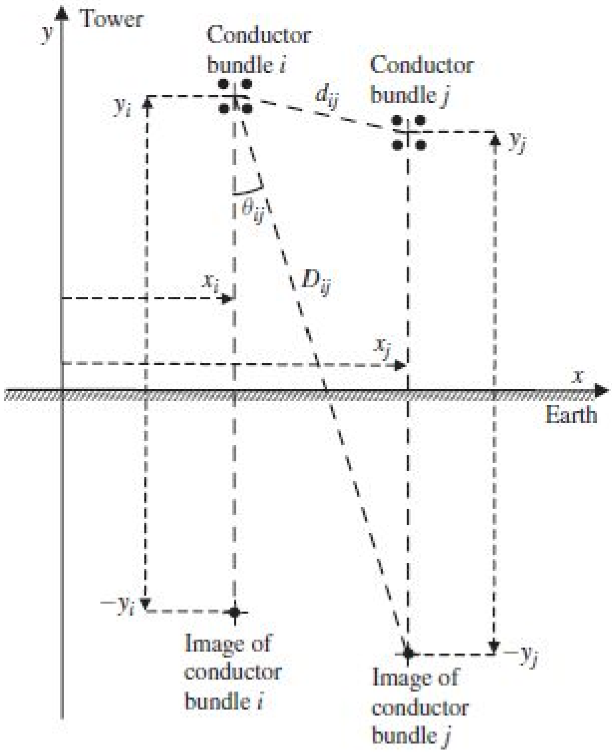

Figure 11: General distribution of the conductors in an overhead line.

On the other hand, the correction terms regarding the earth return path, referring to the mutual impedances, are determined as it can be appreciated below (they are also series equations, but can be simplified due to the same reasoning), in the same units:

$$R_{ij(e)} = \pi^2 10^{-4} f - \frac{f}{911{,}812 \cdot \frac{D_{erc}}{y_i + y_j}} \quad \textbf{(19)}$$

$$X_{ij(e)} = 4\pi 10^{-4} f \cdot log_e\left(\frac{D_{erc}}{D_{ij}}\right) + \frac{f}{911{,}812 \cdot \frac{Derc}{y_i + y_j}} \quad \textbf{(20)}$$

3.1.2.3. Impedance matrix and electric constants

After all the impedance terms are calculated, it is necessary to determine the impedance matrix of the system, which relates the voltages and currents of each phase. The phase impedance matrix, as the line is transposed, is calculated as follows:

$$\mathbf{Z}_{\text{Phase}} = \frac{1}{3}(\mathbf{Z}_{\text{Section-1}} + \mathbf{Z}_{\text{Section-2}} + \mathbf{Z}_{\text{Section-3}}) = \begin{bmatrix} Z_S & Z_M & Z_M \\ Z_M & Z_S & Z_M \\ Z_M & Z_M & Z_S \end{bmatrix}$$

(21)

Where each matrix term can be determined as below:

$$Z_S = \tfrac{1}{3} \cdot (Z_{tt} + Z_{mm} + Z_{bb}) \quad \textbf{(22.1)} \qquad Z_M = \tfrac{1}{3} \cdot (Z_{tm} + Z_{mb} + Z_{bt}) \quad \textbf{(22.2)}$$

Being *t*, *m* and *b* the subscripts for the conductor's position in each section, as can be seen in Figure 8. However, the determination of the phase impedance matrix can be simplified, thanks to the transposition matrix and the ease that Matlab software works with when manipulating vectors and matrices:

$$T = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

(23)

$$Z_{phase} = \tfrac{1}{3} \cdot [Z_{section-1} + T^t \cdot Z_{section-1} \cdot T + T \cdot Z_{section-1} \cdot T^t] \quad \textbf{(24)}$$

After this matrix is determined, it is necessary to convert it into a PNZ reference, as its terms are the ones used in the π-section model, due to their independence between phases. Thus, the rotation matrix is introduced below:

$$\mathbf{H} = \begin{bmatrix} 1 & 1 & 1 \\ h^2 & h & 1 \\ h & h^2 & 1 \end{bmatrix}$$

(25)

$$h = e^{j2\pi/3} = -0,5 + j0,866 \quad \textbf{(26)}$$

Being the final impedance matrix as shown:

$$Z^{PNZ} = H^{-1} \cdot Z_{phase} \cdot H \quad \textbf{(27)}$$

Thus, the resistance and inductance terms introduced in the π-section model are (in Ω):

$$R_\pi = \Re\{Z^{PNZ}(1,1)\}\cdot length \quad \textbf{(28.1)} \qquad L_\pi = \Im\{Z^{PNZ}(1,1)\}\cdot\frac{length}{2\pi f} \quad \textbf{(28.2)}$$

Thanks to phase transposition, the intersequence mutual couplings can be eliminated, resulting on an equal voltage drop for each phase, and hence equal average series self and mutual impedances and susceptances of each phase conductor, which allows the engineer to study a single phase.

3.1.2.4. Stranded conductors

In the case of stranded conductors (i.e. having more than a single wire in each phase), the determination of the impedance terms changes due to the reduction of the effective area. Although this can be seen as a weakness of the line, this measure reduces the harmful skin effect.

Thus, the radius is substituted by the geometric mean radius of the conductor, determined by the following expression (only valid for the impedance terms), in mm:

$$GMR_{c,z} = k\cdot r_o \quad \textbf{(29)}$$

Where *k* is the stranded factor, which depends of the number of conductors per phase. Its values can be found in Annex B. It shall be noted that the distance between conductor wires in the same phase is equal.

3.1.3. Unitary capacitance

The capacitance term will be studied in this section. As well as in the case of the impedance constants, it shall be noted that the parameter introduced in the model is that determined after the calculation of the PNZ susceptance matrix. This matrix will be obtained thanks to the calculation of the Maxwell's potential coefficients of the system, in km/μF, being these:

$$P_{ii} = 17,975109\cdot log_e\left(\frac{2y_i}{r_i}\cdot 10^3\right) \quad \textbf{(30.1)} \qquad P_{ij} = 17,975109\cdot log_e\left(\frac{D_{ij}}{d_{ij}}\right) \quad \textbf{(30.2)}$$

Thus, the phase capacitance and susceptance matrix are as follows, in μF/km and μS/km, respectively:

$$C = P^{-1} \quad \textbf{(31.1)} \qquad B = \omega\cdot C \quad \textbf{(31.2)}$$

Finally, with the same rotation matrix, the PNZ susceptance matrix can be obtained. After this term is determined, the capacitance constant introduced in the π-section model is the following (in F):

$$C_\pi = B^{PNZ}(1,1)\cdot\frac{length\cdot 10^{-6}}{2\pi f} \quad \textbf{(32)}$$

It shall be noted that these equations refer to the case of all the studied materials (i.e. copper, aluminium and ACSR) and dispositions (solid and stranded conductors).

3.2. Electric constants in HVAC cables

In the case of HVAC cable technology, there is a difference in the determination of the electric parameters (i.e. the mathematical equations for the resistance, capacitance, inductance and conductance), due to the different behaviour and geometry present in this technology. Only single-circuit cables are studied in this thesis. The cases studied in this project are onshore and offshore single-core and self-contained cables (in a flat or trefoil disposition, see Figure 12), as well as pipe type systems (which are three-core systems in a triangular distribution, see Figure 13). Only single circuits are considered in this thesis.

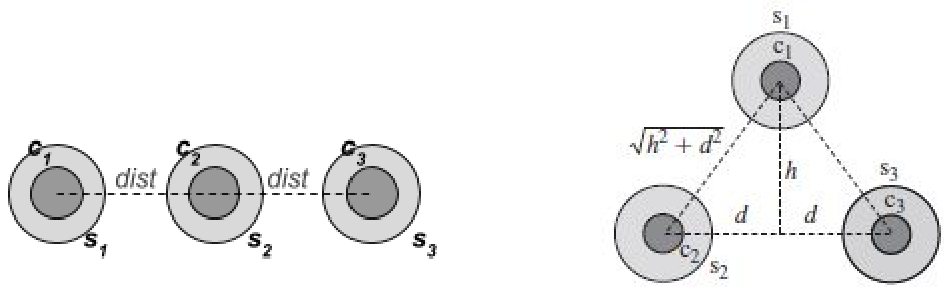

Figure 12: a) Symmetrical flat disposition b) Trefoil disposition, both of single-core cables.

The general geometry for onshore and offshore single-core cables (varying the number of layers, having offshore cables the armour and last insulating layers) is shown in Figure 13, whether the structure of pipe type systems can be appreciated in Figure 14.

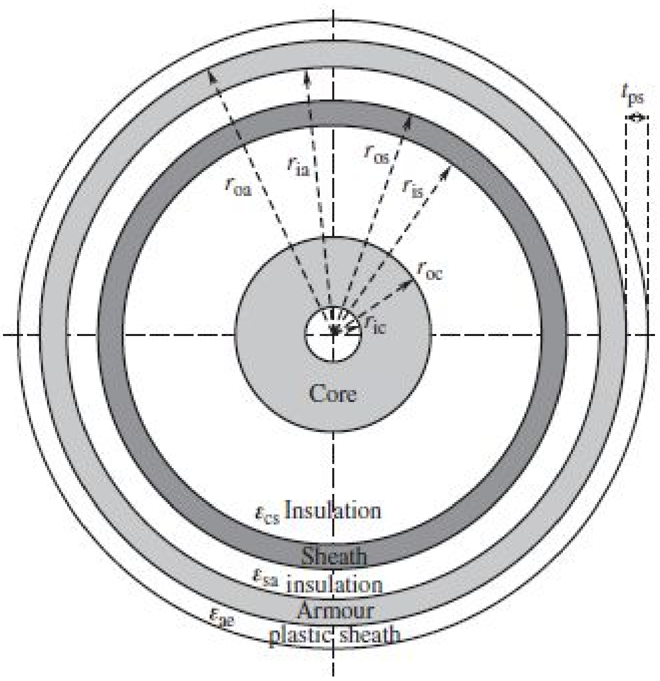

Figure 13: Structure of onshore/offshore cables.

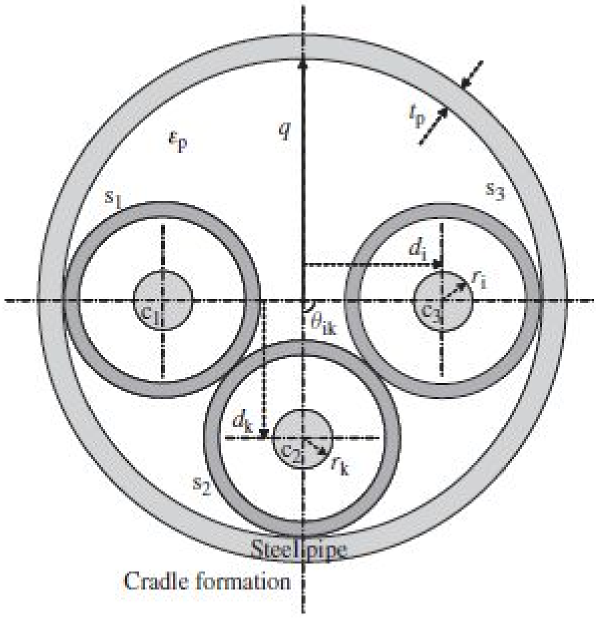

Figure 14: Geometry and distribution of a pipe type cable, having a more centred distribution in this project.[21]

Thus, the following general hypothesis are considered in the calculation of the constants introduced in the π-section model:

- Steady and stable state situation, as this project focuses on this case.
- The conductance term is considered as non-existing, as its value is minimum for frequencies of 50 or 60 Hz in power frequency steady state analysis.
- The distance between adjacent conductors in the flat disposition is considered as constant and equal in all cases, as well as having same buried depth (except for the trefoil distribution).
- There are no sheath overvoltages nor induced screen currents in the entire structure of the cable, thanks to the cross bonding method[22] (being this measure similar to the phases transposition in overhead lines, as seen in Figure 15). Thus, a balance between phases is achieved.

[21] It shall be mentioned that the pipe is as centered as possible, so that *d* and *h* are equal between phases, i.e. $h=d_{k(ij)}$ and $d=d_{i(ij)}$, where $i=1,2,3$ and $i \neq j$ (in this essay).
[22] More information about this measure can be seen in reference number [19] of the bibliography.

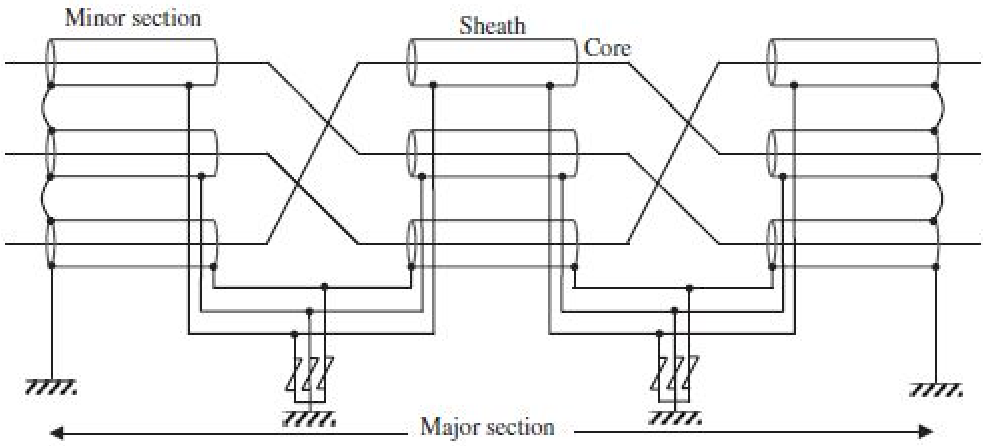

Figure 15: Cross-bonding method, where the cores are perfectly transposed, but the sheaths are not (best arrangement).

- The armour of the cable, when present, is bonded to the sheath. This hypothesis simplifies the determination of the impedance and susceptance matrixes, as will be further appreciated.

- All the conductors have an homogeneous material, as well as the insulating layers. Only coaxial conductors (within a single phase) are considered.

- There is no electrostatic coupling between the phases, due to the earth the screens are connected to, as it acts as an electrostatic shield, only valid for the case of self-contained cables. In pipe type systems, the influence between phases, in terms of capacitance, is not neglectable.

- All the electric parameters are equally distributed along the line, due to the homogenous effect of the ground in their determination. Thus, they are constant and per unit length.

- The influence in the impedance of the sea (in the case of offshore cables) is considered as negligible, as its current return path is poor due to its small conductor properties, as well as having an imprecise calculation method.

Although the influence of the ground is taken into consideration, it must be mentioned that there is a real difficulty in determining the characteristics of a real soil. Regarding this issue, the resistivity of the ground has been considered as 20 **Ω**·m, but can be changed at any moment in the Matlab software.

The cable is therefore defined by the specification of its geometry (distribution of the conductors, dimensions, distance and depth), as well as by its material properties (resistivity and permittivity, amongst others), which allow the determination of the electric constants. As in overhead lines, the π-section model offers good accuracy in order to introduce the electric constants into a further power flow analysis.

3.2.1. Unitary impedance

The resistance, as well as the inductance, will be studied in this section, as they are also directly obtained from the PNZ impedance matrix. Unless mentioned, all the equations refer to single-core self-contained cables (i.e. onshore and offshore cables). Pipe type systems are treated separately.

3.2.1.1. Series self impedance

A three-phase screened cable buried underground or laid in the ocean, the core, sheath and armour (when present) will have a self-impedance with earth return. Thus, these three terms shall be considered.

In the case of the core conductor (this being solid), the self-impedance with earth return is given by (in Ω/km):

$$Z_{cc} = R_{c\,(ac)} + \pi^2 10^{-4} f + j4\pi 10^{-4} f \left[\frac{\mu_c}{4} + log_e\left(\frac{D_{erc}}{r_{oc}} \cdot 10^3 \right) \right] \quad \textbf{(33)}$$

Where μ_c is the relative magnetic permeability of the core conductor, and D_{erc} has been explained in the case of overhead lines.

On the other hand, the self-impedance of the sheath, with earth return path, is as follows, in Ω/km:

$$Z_{ss} = R_{S\,(ac)} + \pi^2 10^{-4} f + j4\pi 10^{-4} f \cdot \left[\frac{\mu_s}{4} \cdot f(r_{os}, r_{is}) + log_e\left(\frac{D_{erc}}{r_{os}} \cdot 10^3 \right) \right] \quad \textbf{(34)}$$

$$f(r_{os}, r_{is}) = 1 - \frac{2r_{is}^2}{(r_{os}^2 - r_{is}^2)} + \frac{4r_{is}^4}{(r_{os}^2 - r_{is}^2)^2} \cdot log_e\left(\frac{r_{os}}{r_{is}} \right) \quad \textbf{(35)}$$

Where μ_s is the relative permeability of the sheath conductor.

Finally, the self-impedance of the armour (only in the case of offshore cables) is, in Ω/km:

$$Z_{aa} = R_{a\,(ac)} + \pi^2 10^{-4} f + j4\pi 10^{-4} f \cdot \left[\frac{\mu_a}{4} \cdot f(r_{oa}, r_{ia}) + log_e\left(\frac{D_{erc}}{r_{oa}} \cdot 10^3 \right) \right] \quad \textbf{(36)}$$

Where μ_a is the relative magnetic permeability of the armour. In the Matlab modelling programs, each material of the conductors material can be chosen.

3.2.1.1.1. AC resistance

The AC resistance term, present on each self-impedance equation, takes into account the influence of the skin and proximity effects, as well as the different geometries available (i.e. whether the conductors are stranded or not, annular, etc.).

Thus, this term is calculated as follows in the present project (in Ω/km):

$$R_{(ac)} = R_{(dc)} \cdot [1 + k_s + k_p] \quad \textbf{(37)}$$

$$R_{(dc)} = \frac{1000\rho}{A} \cdot [1 + \alpha_{20} \cdot (T - 20)] \quad \textbf{(38)}$$

Being ϱ the resistivity of the studied conductor, in $\Omega \cdot mm^2/m$, and k_s and k_p the coefficients of the skin and proximity effects, respectively. These terms are explained below, as they depend on the geometry of the conductor:

- Skin effect term:

$$k_S = \begin{cases} \dfrac{z^4}{0.8 \times z^4 + 192} & 0 < z \leq 2.8 \\ 0.0563 \times z^2 - 0.0177 \times z - 0.136 & 2.8 < z \leq 3.8 \\ 0.354 \times z - 0.733 & z > 3.8 \end{cases}$$

(39)

$$z = \sqrt{8\pi f a_z / (10^4 \cdot R_{dc})} \quad \textbf{(40)}$$

Where a_z takes into consideration the shape and distribution of the wires in each phase. In the case of this study, $a_z=1$ (stranded and/or circular solid conductors), or follows the equation below, in the case of annular conductors:

$$a_z = [(r_o - r_i)/(r_o + r_i)][(r_o + 2r_i)/(r_o + r_i)]^2 \quad \textbf{(41)}$$

- Proximity effect term (only the case of three single-core cables:

$$k_p = F(p) \cdot \left(\frac{d_c}{S}\right)^2 \cdot \left[0,312 \cdot \left(\frac{d_c}{S}\right)^2 + \frac{1,18}{F(p)+0,27}\right] \quad \textbf{(42)}$$

$$F(p) = \frac{p^4}{0,8 \cdot p^4 + 192} \quad \textbf{(43.1)} \qquad p = \sqrt{\frac{8\pi f a_p}{10^4 R_{dc}}} \quad \textbf{(43.2)}$$

Where d_c is the diameter of the conductor, S is the axial spacing between conductors, and a_p is equal to 0,8 in this project (circular solid and annular conductors).

3.2.1.2. Mutual impedance

The mutual impedance between the different conductor layers can be determined as follows, in Ω/km:

$$Z_{ij} = \pi^2 10^{-4} f + j4\pi 10^{-4} f \cdot log_e\left(\frac{D_{erc}}{S_{ij}} \cdot 10^3\right) \quad \textbf{(44)}$$

Where S_{ij} is the distance between the centres of cables *i* and *j* if the conductors belong to different phases, in mm. When the conductors belong to the same cable, this term is calculated as the geometric mean distance between these two conductors.

3.2.1.3. Pipe type impedance terms

In the case of pipe type cables, the calculation of the impedance parameters is different due to the geometry and disposal of the conductors, being different the influence between them. Moreover, this difficulty in the determination of the parameters is also due to the non-linear permeability of the pipe[23], which is normally constituted by steel. In this study, the pipe is the only current return path besides the sheaths of the three cables, which means that no current returns through the earth. In order to accomplish this, it is necessary to assume a pipe of an infinite thickness[24].

In the mathematical model, this is equal to consider a resistivity of ϱ_p=3,8·10^{-8} Ω·m, relative permeability of μ_p=400 and a thickness of 6,3 mm, resulting in a depth of penetration of 1,32 mm, smaller than the dimensions of the pipe. Thus, the self-impedance matrix of cable phase *k* is the following:

$$Z_k = \begin{bmatrix} Z_{cc-k} & Z_{cs-k} \\ Z_{cs-k} & Z_{ss-k} \end{bmatrix} = \begin{bmatrix} Z_1 + Z_2 + Z_3 + Z_4 + Z_5 - 2Z_6 & Z_4 + Z_5 - Z_6 \\ Z_4 + Z_5 - Z_6 & Z_4 + Z_5 \end{bmatrix}$$

(45)

Being the different terms, all in Ω/km:

$$Z_1 = \frac{\rho_c}{2\pi r_c} \cdot (\sqrt{2} \cdot \delta^{-1} \cdot e^{j\pi/4}) \cdot \frac{I_o[(\sqrt{2}\delta^{-1} \cdot r_c) \cdot e^{j\pi/4}]}{I_1[(\sqrt{2}\delta^{-1} \cdot r_c) \cdot e^{j\pi/4}]} \quad \textbf{(46)}$$

$$Z_2 = j4\pi f 10^{-4} log_e\,(r_{is}/r_c) \quad \textbf{(47)}$$

$$Z_3 = \frac{\rho_s m}{2\pi r_{is} D}[I_o(mr_{is})K_1(mr_{os}) + K_o(mr_{is})I_1(mr_{os})] \quad \textbf{(48)}$$

$$Z_4 = \frac{\rho_s m}{2\pi r_{os} D} \cdot [I_o(mr_{os})K_1(mr_{is}) + K_o(mr_{os})I_1(mr_{is})] \quad \textbf{(49)}$$

---

[23] This non-linear permeability varies the magnitude of the ZPS current, diminishing the ZPS impedance term. Thus, the assumption explained below (i.e. an infinite pipe thickness) is necessary in order to calculate the impedance terms.
[24] Hypothesis found in reference number [12] of the bibliography (section 3.3.3, page 152).

$$Z_5 = j4\pi f 10^{-4} log_e\left(\frac{q^2-d_k^2}{qr_{os}}\right) \quad \textbf{(50)}$$

$$Z_6 = \frac{1000\rho_s}{2\pi r_{is} r_{os} D} \quad \textbf{(51)}$$

$$m = \sqrt{2}\delta^{-1} e^{j\pi/4} \quad \textbf{(52)}$$

$$D = I_1(mr_{os})K_1(mr_{is}) - K_1(mr_{os})I_1(mr_{is}) \quad \textbf{(53)}$$

Being ϱ_s the resistivity of the sheath. Besides, the impedance terms of the pipe ought to be considered as well, which are shown below.

- Pipe's internal impedance with return path the inside wall of it, in Ω/km:

$$Z_{p-int} = j4\pi f \mu_p 10^{-4} \left\{ \frac{K_o(mq)}{mqK_1(mq)} + 2\sum_{n=1}^{\infty}\left[\left(\frac{d_i}{q}\right)^{2n} \cdot \frac{K_n(mq)}{n\mu_p K_n(mq) - K_n'(mq)}\right]\right\} \quad \textbf{(54)}$$

- Mutual impedance between the *i*th and *k*th conductor respect the inner wall of the pipe, in Ω/km:

$$Z_{i-k} = j4\pi f 10^{-4} \left\{ \frac{\mu_p K_o(mq)}{mqK_1(mq)} + log_e\left[\frac{q}{\sqrt{d_i^2+d_k^2-2d_id_k cos\theta_{ik}}}\right] + \sum_{n=1}^{\infty}\left(\frac{d_id_k}{q^2}\right)^n \cdot cos(n\theta_{ik}) \cdot \left[2\mu_p \cdot \frac{K_n(mq)}{n\mu_p K_n(mq) - mqK_n'(mq)} - \frac{1}{n}\right]\right\}$$
(55)

Being *q* the inner radius of the steel pipe (in mm), d_k=*h* the height of the triangle formed by the union of the cores (in mm, see Figure 13), d_i=*d* half the distance between adjacent cables 1 and 3 (in mm), and ε_p the permittivity of the insulation located inside the pipe's wall. These impedance are equal between the three phases due to their almost perfect equilateral triangle disposition.

It shall be noted that the derivative terms were approximated in the Matlab programs, with the following equation:

$$K_n'(mq) = \frac{K_{n-1}(mq) - K_{n+1}(mq)}{2} \quad \textbf{(56)}$$

Besides, the sum terms were simplified, with limits from *n=1* to *n=100*, values which offer a good approximation, as well as a small time of computation.

3.2.1.4. Impedance matrix

After all the impedance terms are calculated, it is necessary to determine the sequence impedance matrix of the system. The phase impedance matrix, which is calculated prior to the PNZ elements, depends on the geometry of the cable, as well as the distribution of the layers. Thus, each case must be studied separately.

- **Cables without armour, flat formation**. This is the case of the onshore cables in this disposition. It is necessary to distinguish between cables in flat symmetrical formation and in trefoil distribution, as the mutual terms differ due to the distance between phases. Thus, the impedance matrix is the one that follows (in Ω/km):

$$\mathbf{Z} = \frac{1}{3}\left[\begin{array}{ccc|ccc} 3e & b+c+d & b+c+d & a+b+d & a+b+c & a+c+d \\ b+c+d & 3e & b+c+d & a+b+d & a+b+c & a+c+d \\ b+c+d & b+c+d & 3e & a+b+d & a+b+c & a+c+d \\ \hline a+b+d & a+b+d & a+b+d & 3f & 3b & 3d \\ a+b+c & a+b+c & a+b+c & 3b & 3f & 3c \\ a+c+d & a+c+d & a+c+d & 3d & 3c & 3f \end{array}\right]$$

(57)

Where the different terms are:

$$a = Z_{CiSi} \qquad b = Z_{C1C2} = Z_{C1S2} = Z_{S1S2} \quad \textbf{(58.1)} \ \textbf{(58.2)}$$
$$c = Z_{C2C3} = Z_{S2C3} = Z_{S2S3} \qquad d = Z_{C1C3} = Z_{C1S3} = Z_{S1S3} \quad \textbf{(58.3)} \ \textbf{(58.4)}$$
$$e = Z_{CiCi} \qquad f = Z_{SiSi} \quad \textbf{(58.5)} \ \textbf{(58.6)}$$

Thus, the phase matrix is the following (in Ω/km):

$$Z_{phase} = Z_{cc} - Z_{cs} \cdot Z_{ss}^{-1} \cdot Z_{cs}^{t} \quad \textbf{(59)}$$

Where Z_{cc} and Z_{cs} are the submatrixes shown in (57), in first and second positions. Thus, the PNZ term is:

$$Z^{PNZ} = H^{-1} \cdot Z_{phase} \cdot H \quad \textbf{(60)}$$

- **Cables without armour, trefoil formation**. This is the case of onshore cables in this triangular disposition. Thus, the voltages and currents in each conductor are related thanks to the impedance matrix, shown below (in Ω/km):

$$\left[\begin{array}{c} V_{C1} \\ V_{C2} \\ V_{C3} \\ \hline V_{S1} \\ V_{S2} \\ V_{S3} \end{array}\right] = \begin{array}{c} \\ \mathrm{C1} \\ \mathrm{C2} \\ \mathrm{C3} \\ \mathrm{S1} \\ \mathrm{S2} \\ \mathrm{S3} \end{array} \begin{array}{c} \mathrm{C1}\ \mathrm{C2}\ \mathrm{C3}\ \mathrm{S1}\ \mathrm{S2}\ \mathrm{S3} \\ \left[\begin{array}{ccc|ccc} e & b & b & a & b & b \\ b & e & c & b & a & c \\ b & c & e & b & c & a \\ \hline a & b & b & f & b & b \\ b & a & c & b & f & c \\ b & c & a & b & c & f \end{array}\right] \end{array} \left[\begin{array}{c} I_{C1} \\ I_{C2} \\ I_{C3} \\ \hline I_{S1} \\ I_{S2} \\ I_{S3} \end{array}\right]$$

(61)

In this case, *b* is equal to the *d* term previously stated, as the distance is the same. The calculation of the sequence impedance matrix is the same as before.

- **Cables with armour**. In the case of single-core offshore cables, the impedance phase matrix in flat symmetrical and trefoil formations is similarly calculated, as the different dispositions have been previously taken into account. Thus, the voltages and currents are related as follows (it shall be noted that $V_S=V_A=0$ due to these elements are earthed at both ends, but the expressions below also work well otherwise):

$$\begin{bmatrix} \mathbf{V}_{C(3\times1)} \\ \mathbf{0}_{S,A(6\times1)} \end{bmatrix} = \begin{bmatrix} \mathbf{Z}_{CC(3\times3)} & \mathbf{Z}_{CS,CA(3\times6)} \\ (\mathbf{Z}_{CS,CA(3\times6)})^t & \mathbf{Z}_{SS,AA(6\times6)} \end{bmatrix} \begin{bmatrix} \mathbf{I}_{C(3\times1)} \\ \mathbf{I}_{S,A(6\times1)} \end{bmatrix}$$

(62)

Thus, the phase impedance matrix is (in Ω/km):

$$Z_{phase} = Z_{CC_{(3x3)}} - Z_{CS,CA_{(3x6)}} \cdot Z_{SS,AA_{(6x6)}}^{-1} \cdot \left(Z_{CS,CA_{(3x6)}}\right)^t$$

(63)

The sequence impedance matrix can be calculated as previously shown. It shall be noted that, in this case, the PNZ matrix is not diagonal, as there are intersequence terms, which do not affect to the Z^{PP} impedance.

- **Pipe type cables**. Considering pipe type cables, the phase matrix is similar as that previous to the Z_{phase} in the case of armoured systems. The influence between the metallic pipe and the other conductors of the phase can be seen in the formula below (in Ω/km):

$$Z_{phase} = \begin{array}{c} \begin{bmatrix} Z_{cc-k} & Z_{cs-k} & Z_{i-k} \\ Z_{cs-k} & Z_{ss-k} & Z_{i-k} \\ Z_{i-k} & Z_{i-k} & Z_{p-int} \end{bmatrix} \end{array} \begin{array}{l} Core \\ Sheath \\ Pipe \end{array}$$

(64)

Thus, thanks to the rotation matrix, the sequence impedance matrix is obtained. In this case, the PNZ matrix is not diagonal, as in the offshore cables.

Finally, the electric constants introduced in the π-section model (in Ω) are the following, in all the studied cases:

$$R_\pi = \Re\{Z^{PNZ}(1,1)\} \cdot length \quad \textbf{(65.1)} \qquad L_\pi = \Im\{Z^{PNZ}(1,1)\} \cdot \frac{length}{2\pi f} \quad \textbf{(65.2)}$$

3.2.2. Unitary capacitance

The capacitance term of single-core screened cables will be studied in this section. As well as in the case of overhead lines, the parameter introduced in the model is that determined after the calculation of the PNZ susceptance matrix.

As stated in the hypothesis of this transmission technology, there is no mutual capacitance (no electrostatic coupling) among the three phases in the case of individually screened cores. Thus, the different terms are calculated as shown below.

The capacitance between the core and sheath, due to the effect of the first insulation layer, is as follows, in μF/km/phase:

$$C_{cs} = \frac{0{,}0556325 \cdot \varepsilon_{cs}}{\log_e\left(\frac{r_{is}}{r_{oc}}\right)} \quad \textbf{(66)}$$

On the other hand, the capacitance between the sheath and the armour (in the case of offshore cables), due to the presence of the second insulating layer, is determined as follows, in μF/km/phase:

$$C_{sa} = \frac{0{,}0556325 \cdot \varepsilon_{sa}}{\log_e\left(\frac{r_{ia}}{r_{os}}\right)} \quad \textbf{(67)}$$

Finally, the capacitance term between the armour and the earth (offshore cables), or between the sheath and the earth (onshore cables), is calculated following the equation below, in μF/km/phase:

$$C_{ae} = \frac{0{,}0556325 \cdot \varepsilon_{ae}}{\log_e\left(\frac{r_{oa}+t_{ps}}{r_{oa}}\right)} \quad \textbf{(68)}$$

As the cables are solidly bonded and cross-bonded, the sheaths can be mathematically eliminated, resulting on a negligible C_{se} capacitance term, despite having an insulating layer between these and the earth.

3.2.2.1. Pipe type capacitance terms

In the case of pipe type cables, the capacitance terms inside a phase (i.e. the self terms) are the same, as the layer disposal does not change. However, the influence in the capacity between phases is different due to the presence of the pipe, as well as because of the disposition of the cables inside of it (i.e. three-core systems). Thus, the calculation of these terms becomes more complex, being these the capacitance between the sheaths of the three phases, and between the enclosures and the pipe, respectively, as shown below (in μF/km/phase):

$$C_{ss\,(ik)} = \frac{0{,}0556325 \cdot \varepsilon_p}{\log_e\left[\frac{q}{\sqrt{d_i^2+d_k^2-2d_i d_k \cos\theta_{ik}}}\right] - \sum_{n=1}^{\infty}\left(\frac{d_i d_k}{q^2}\right)^n \cdot \frac{\cos(n\theta_{ik})}{n}} \quad \textbf{(69)}$$

$$C_{sp\,(ii)} = \frac{0{,}0556325 \cdot \varepsilon_p}{\log_e\left(\frac{q^2-d_i^2}{q \cdot r_i}\right)} \quad \textbf{(70)}$$

Where q is the inner radius of the steel pipe (in mm), h the height of the triangle formed by the union of the cores (in mm, see Figure 13), d half the distance between adjacent cables 1 and 3 (in mm), and ε_p the permittivity of the insulation located inside the pipe's wall.

In this project, the calculation of these terms is simplified due to the fact that the angle between the pipe's centre and the centres of cables (Θ_{ik}, in radians) is approximately $\pi/2$ rad, due to the disposition of the phases. As in the other equations of pipe type cables, the sum has been approximated by also taking $n=1$ to $n=100$ as its limits.

It must be mentioned that the presence of the pipe does not introduce any additional susceptance term, as no current returns through the earth (i.e. the pipe is the return path).

3.2.2.2. Susceptance matrix

As in the case of the determination of the impedance matrix, it is necessary to differ between cables with and without armour. Thus, the phase matrixes are firstly calculated, in order to further obtain the PNZ parameters.

- **Screened cables with no armour**. This is the case of screened single-core onshore cables, in a flat disposal as well as in a trefoil formation. It ought to be noted that there is no capacitance between one phase and another, as it can be appreciated in the matrixes. As the sheaths are eliminated (cross-bonded cables), the phase susceptance matrix can be obtained as follows:

$$\mathbf{B}_{\text{Phase}} = \begin{bmatrix} B_{CS} & 0 & 0 \\ 0 & B_{CS} & 0 \\ 0 & 0 & B_{CS} \end{bmatrix}$$

(71)

$$B_{cs} = \omega \cdot C_{cs} \quad \textbf{(72)}$$

The corresponding shunt sequence susceptance matrix is the following (in µS/km):

$$B^{PNZ} = B_{phase} \quad \textbf{(73)}$$

- **Screened cables with armour**. In this sort of cables (i.e. offshore systems, in a flat or trefoil formation), there are three insulating layers, and therefore three capacitance terms. As the sheaths and armours (not as the cores, which are not due to the cross-bonding method) are usually earthed at both ends of the line, the matrix is greatly simplified, and equal to the previous B_{phase} matrix (screened cables without armour). This is due to the circulation currents, which flow through the sheath and armour in parallel with earth return.

  However, when the sheaths and armours of the three phases are not bonded and earthed at both ends, the susceptance is determined as shown below (in μS/km), which is equal to the PPS, NPS and ZPS terms (i.e. diagonal terms of the PNZ matrix):

$$B_{phase} = \frac{1}{\frac{1}{B_{cs}}+\frac{1}{B_{sa}}+\frac{1}{B_{ae}}} \quad \textbf{(74)}$$

  Both cases are considered in the Matlab programs of offshore cables.

- **Pipe type cables**. As in the case of the sequence impedance matrix calculation, the geometry of this sort of cables, as well as the conductor's distribution, makes it necessary to determine the susceptance matrix differently. Thus, this calculation is done considering the pipe as a not earthed conductor, as its influence among the other phases is not negligible. The first matrix is as follows (in μS/km):

$$B = \begin{array}{c} \begin{bmatrix} B_{cs} & 0 & 0 & -B_{cs} & 0 & 0 & 0 \\ 0 & B_{cs} & 0 & 0 & -B_{cs} & 0 & 0 \\ 0 & 0 & B_{cs} & 0 & 0 & -B_{cs} & 0 \\ -B_{cs} & 0 & 0 & B_{cs} & -B_{ss} & -B_{ss} & -B_{sp} \\ 0 & -B_{cs} & 0 & -B_{ss} & B_{cs} & -B_{ss} & -B_{sp} \\ 0 & 0 & -B_{cs} & -B_{ss} & -B_{ss} & B_{cs} & -B_{sp} \\ 0 & 0 & 0 & -B_{sp} & -B_{sp} & -B_{sp} & 0 \end{bmatrix} \end{array} \begin{array}{l} cores \\ \\ \\ sheaths \\ \\ \\ pipe \end{array}$$

(75)

  Thus, this term is transformed to the phase matrix, thanks to the following expression:

$$B_{phase} = B_{CC_{(3x3)}} - B_{CS,CP_{(3x4)}} \cdot B_{SS,PP_{(4,4)}}^{-1} \cdot \left(B_{CS,CP_{(3,4)}}\right)^{t} \quad \textbf{(76)}$$

  The sequence susceptance matrix can be calculated thank to the rotation matrix, similarly to the case of the impedance term.

Finally, the capacitance constant introduced in the π-section model (in F) is the following, in all the studied cases:

$$C_{\pi} = B^{PNZ}(1,1)\cdot\frac{length\cdot 10^{-6}}{2\pi f} \quad \textbf{(77)}$$

3.3. Electric constants in HVAC Gas Insulated Lines

The study of this technology has been simplified to the case of cables in this thesis, as the related bibliography provided a model too complex for the inclusion in this thesis. The reader is then remitted to Annex F: Effect of the ground on GIL, as well as to reference number [20] of the bibliography for further information about this topic. It is therefore necessary to understand the functioning, as well as the behaviour, of each element in cable lines.

Thus, in this sort of HVAC transmission systems, the determination of the electric parameters (i.e. the mathematical equations for the resistance, capacitance, inductance and conductance), is almost equal to the case of single-core cable lines, due to the similar behaviour of the different layers in a phase, as well as due to their geometry. Thus, this project aims to study the same alternatives as in cable lines, as the modelling programs are the same, but with little changes (such as some of the hypothesis or the material in the insulation layer, which does not affect the modelling equations).

As it has been previously stated, a typical gas insulated line does not have any outer armour. Therefore, the modelling programs of offshore cables are not appropriate in this technology. Thus, the general geometry of GIL is shown in Figure 16: a solid core conductor, an insulation layer constituted by gas (normally 80% N_2 and 20% SF_6), and an outer sheath or enclosure. An outer insulation layer can be found in some cases, which does not affect to the calculation of the RLC parameters, as the sheaths are directly bonded to the earth.

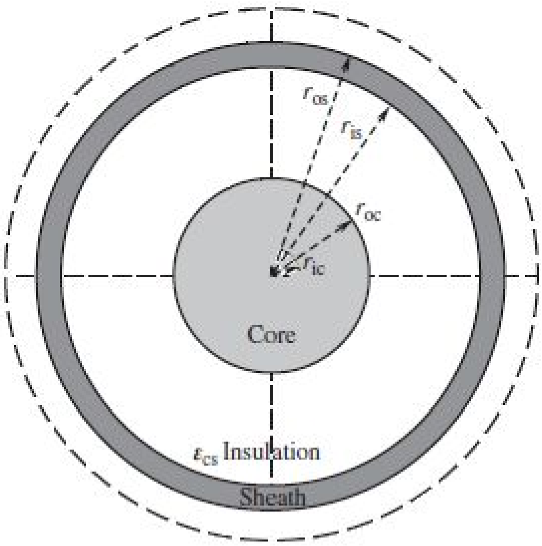

Figure 16: General geometry of a Gas Insulated Line.

Then, the general hypothesis in the calculation of the constants introduced in the π-section model are very similar as in cable systems, with some differences. Thus, the assumptions made in this section are the following:

- Steady and stable state situation.

- The conductance term is considered as non-existing, as its value is minimum for frequencies of 50 or 60 Hz in power frequency steady state analysis.

- As a distinctive aspect of this technology, the permittivity of the insulating layer must correspond to a gas, instead of the typical insulating solid materials, such as PVC, XLPE, EPR or paper. Moreover, this gas material is considered as homogeneous and an ideal insulator.

- The distance between adjacent conductors is considered as constant and equal in all cases, as well as having same buried depth (except for the trefoil disposition).

- There are no sheath overvoltages nor induced screen currents in the entire structure of the cable, also thanks to the cross bonding method. Moreover, the line is grounded at both ends, being the sheaths mutually bonded to the soil (as well as the outer insulating layers, when present).

- Only coaxial conductors (within a single phase) are considered.

- There is no electrostatic coupling between the phases, due to the earth the enclosures are connected to, as it acts as an electrostatic shield. Moreover, the sheaths are at zero potential, a justifiable hypothesis due to practical experience: the structure of this technology allows the user to safely touch the cable. Thus, the effect of the ground can be negligible.

- The self and mutual influences of the ground in the transmission system has been considered as negligible, due to the difficulty of its determination. However, a brief theoretical study is included in Annex E: Effect of the ground in GIL.

- All the electric parameters are equally distributed along the line, due to the equal distribution and influence between components at any point of the system. Moreover, they are constant and per unit length.

The gas insulated cable is defined by the same specifications as the cables explained in the previous section. Therefore, the impedance and capacitance equations and matrices are equal to those explained in chapter 3.2 (excluding the offshore and pipe type cables). However, the permittivity used in equation (66) is that corresponding to the gas mixture (see the Matlab modelling function, or Annex D).

4. Description of the modelling tool

This chapter aims to explain how the modelling equations were introduced in the Matlab programs, as well as their functioning (i.e inputs and outputs, amongst other considerations).

It is necessary to mention that the initial idea of this project was to be able to define each technology thanks to the specification of the nominal current, voltage and power (taking into consideration the available normatives). Thus, the modelling of each transmission system is accomplished by defining the geometry and arrangement of the conductors, as well as the materials of each layer. It is then supposed that the geometry is obtained thanks to Matlab calculation functions previously used, which will not be covered in this thesis.

The outputs of these Matlab programs will be introduced in a further power flow analysis, obtained thanks to Matlab software. Figure 17 shows a flux diagram of the steps followed in the execution of a power flow analysis:

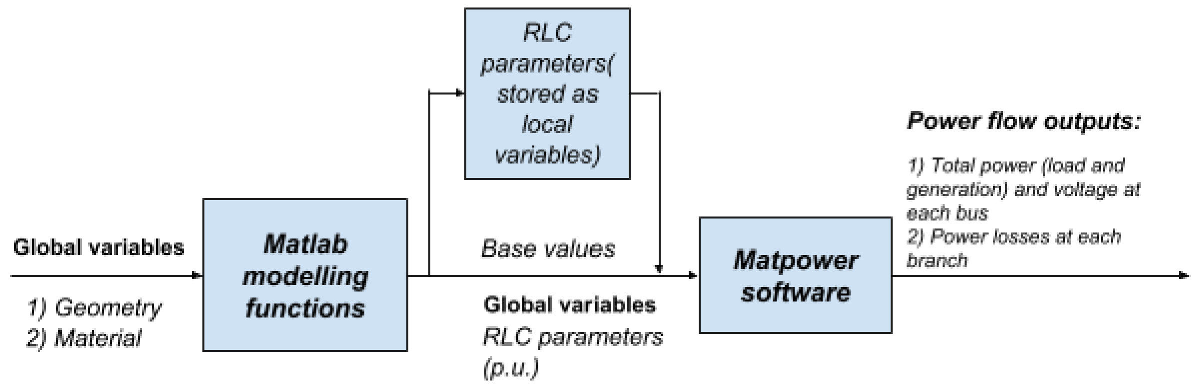

Figure 17: Flux diagram showing the functioning of the own Matlab functions and Matpower software.

It shall be mentioned that the modelling Matlab programs were specifically written in order to obtain the RLC parameters in per unit (pu) values[25], as well as the other necessary terms that the Matpower software may demand, such as the active and reactive power of the load and the base values (i.e. voltage and power).

The different structure and functioning of the programs regarding overhead lines, cables and GIL are explained in this chapter.

[25] See how to obtain these values in the reference number [21] of the bibliography (chapter 1.3).

4.1. Matlab functions for HVAC overhead lines

This section aims to properly explain how to elaborate a π-section model for HVAC overhead lines thanks to the Matlab programs, by calculating its characteristic constants (i.e. unitary resistance, inductance, capacitance and conductance), taking into consideration each option this technology offers, which have been previously explained. This obtained model is therefore specifically conceived to be introduced in the already existing Matpower tools, as previously stated, with the purpose of studying its behaviour (for example, the voltages of all the electric buses, as well as their generated or consumed power) in a more realistic situation. All the information about power flow will be explained in chapter 5.

These different four alternatives are shown below, each belonging to an own Matlab modelling program[26], as they differ in the equations and in the inputs the function may demand. It shall be noted that all of them are transposed, due to this measure is the most common nowadays.

- Transposed solid lines, with copper and aluminium as conductor materials. This option is the simplest, as it only considers a single conductor per phase, without any steel reinforcement. Thus, the related designing file is *OHL_transposed_solid.m*.

- Transposed solid lines, considering ACSR as the main conductor material. This alternative needs other modelling equations and inputs, as the main conductor is the aluminium surrounding the steel core (which provides resistance to traction to the line). The modelling file is *OHL_transposed_solid_ACSR.m*.

- Transposed stranded lines, with copper and aluminium as conductor materials. In order to reduce the skin effect, the measure of disposing more than one wire per phase is considered. Thus, the related Matlab program considers this sort of overhead lines, being named as *OHL_transposed_stranded.m*.

- Transposed stranded lines, considering ACSR as the conductor. This options is similar as the previous one, changing the material and thus, several equations due to the geometry of the wires (considered as hollow conductors). The related Matlab file is *OHL_transposed_stranded_ACSR.m*.

It shall be mentioned that these modelling programs consider a medium-length HVAC line (due to the considered π-section model), located in the European area (it ought to be remembered that U.S.A. lines have a frequency of 60 Hz[27]). Therefore, although the length of the line is variable (as it is one of the inputs), reasonable values must be considered (i.e. comprised between 50 and 250 km).

[26] These Matlab programs can be found in Annex D: Matlab files for the modelling and study of transmission lines.
[27] However, the frequency of the line can be manually changed in the programs.

Moreover, thanks to the definition of the distances between phases in the line (from the center of the tower, see Figure 11), most of the existing transmission overhead systems can be studied, such as flat, concentric, delta, offset and vertical towers, amongst other.

In order to make this modelling software more simple and accessible, a parent (or main) function was created. This program, named *OHL()*, takes as inputs all of those present in the previous modelling files, selecting the correct case thanks to the values of these variables. The main function returns the requested outputs that the Matpower files require.

The structure of each modelling file is explained in the following sections, as well as the input variables they may demand.

4.1.1. Functions for transposed solid lines

This section will be divided into two different cases, regarding the material used for the transmission of the electric power. The related files are *OHL_transposed_solid.m* and *OHL_transposed_solid_ACSR.m*. Each modelling program needs its own inputs, being these defined as global variables, in order to be able to access them afterwards, i.e. in the Matpower software.

However, these two Matlab functions have several common inputs, shown in Table 3. The meaning of each input is also explained in the related files.

These programs give the RLC parameters (in Ω) as local outputs. However, when the parent function *OHL()* is called, it chooses the correct case and gives the results, which are the values of the load and the RLC parameters in per unit values. Thus, these global outputs are shown in Table 4. It shall be mentioned that these variables are common in each modelling parent function (i.e. *OHL.m* and *cables.m*).

Variable name	Definition and units
r	External radius of a single conductor, in mm
y_t, y_m, y_b	Height of the first, second and third phase conductors, in m (see Figure 11)[28]
x_t, x_m, x_b	Distance between the first, second and third phase conductors and the center of the tower, in m
len	Total length of the line, in km

Table 3: Inputs in transposed solid lines.

[28] Taking into consideration the first section of the transposed line, i.e. the case in which the first phase occupies the *t* position (top), the second conductor is in the *m* (middle) position and the third, in the remaining, *b* (bottom).

Variable name	Definition and units
S_o[29]	Total power generated by at the beginning of the line, in MVA
S_f	Power consumed at the end of the line, in MVA
R_{pu}	Value of the resistance parameter in the π-section model, in p.u. thanks to the equations: $R_{pu} = \frac{R_{pi}}{Z_b}$ $\quad Z_b = \frac{V_b^2}{S_b}$
X_{pu}	Value of the inductance parameter in the π-section model, in p.u. thanks to the equation: $X_{pu} = 2\pi \cdot 50 \cdot \frac{L_{pi}}{Z_b}$
B_{pu}	Value of the capacitance parameter in the π-section model, in p.u. thanks to the equation: $B_{pu} = B_{pi} \cdot Z_b$

Table 4: Outputs of the modelling programs.

As it will be further detailed, Matpower demands other parameters besides the shown in Table 4, such as the base power and voltage[30]. However, these values ought to be manually introduced, as they are not used in the modelling of the transmission system at any time.

In the case of copper and aluminium lines, there is a single specific input: the material used for modelling the transmission system, defined as *mat*, where the user can choose between those two by indicating *mat=1* (aluminium) or *mat=2* (copper). Thus, the hypothesis and equations used in this sort of systems are explained in chapter 3.1. Moreover, the code of this program can be found in Annex D: Matlab files for the modelling and study of transmission lines.

Finally, when ACSR overhead lines are considered, the only specific input is the inner radius of the aluminium layer, named r_i, in mm. It shall be noted that the determination of the self-impedance term in the phase is different due to the geometry of the conductor, as stated in equation (10).

[29] Obtained thanks to the transmission matrix. See more details of its use in Matpower in section 5.2.3.
[30] This base parameter is well defined for HV systems, with values such as 132 kV, 220 kV and 400 kV.

4.1.2. Functions for transposed stranded lines

This project consider two alternatives regarding the modelling of stranded conductors, i.e. depending on the material used, as in the previous section. The related files are *OHL_transposed_stranded.m* and *OHL_transposed_stranded_ACSR.m*. Table 3 shows the common inputs these functions have, as well as the *n* input variable, with which the user can determine the number of conductors per phase of the stranded line.

It shall be noted that, in this sort of transmission lines, the geometric mean radius term is used in the calculation of the impedance and capacitance terms (as explained in section 3.1.2.4), instead of the radius of the conductors.

4.2. Matlab functions for HVAC cables and gas insulated lines

In this section, the different modelling options and programs for the cable and gas insulated technologies (as both are similar) are detailed. This obtained model (i.e. π-section) will be also introduced in a power flow analysis (chapter 5), in order to study these lines in a realistic situation.

These different five modelling options shown below belong to an own Matlab modelling program, as they differ in the equations and in the inputs the function may demand, due to the different geometries and distribution of the phases.

- Onshore single-core cables in flat arrangement. The related Matlab file, *onshore_SC_flat.m*, considers symmetrical distance between phases. Each cable lacks from a metallic armour, as they need no traction reinforcement. It shall be remembered that every modelling alternative consider the method of cross-bonding, in order to achieve balance between phases.

- Onshore single-core cables in a trefoil disposition. This arrangement can be appreciated in Figure 12b, where the cables form a non equilateral triangle. The related Matlab program is *onshore_SC_trefoil.m*.

- Offshore single-core cables in flat arrangement. This modelling option is similar to the first case, having each cable two additional elements: the armour and outer insulating layer. Thus, the related program, *offshore_SC_flat.m*, has two additional inputs, which will be further explained.

- Offshore single-core cables in a trefoil placement. The phases form an equilateral triangle, but having each the two additional layers explained before. The Matlab file for this modelling options is *onshore_SC_trefoil.m*.

- Pipe type cables. This option considers three-core cables, as all the phases are contained in a single pipe (see Figure 14). Thus, the system has a trefoil arrangement. The related program is *PT_triangle.m*, as the self and mutual influence of the pipe has been taken into consideration, changing the equations needed in the modelling of this technology.

These modelling programs consider a medium-length line, but the π-section nominal model can be changed to the π-section exact model by changing the coefficients of the transmission matrix in the studied file. Thus, although the length of the line is variable, reasonable values for the existing model must be considered, so a good accuracy is achieved.

As stated in previous sections, the existing Matlab files can also be applied in the modelling of gas insulated lines, as the geometry and behaviour of these systems are very similar. However, it is appealing to only use the functions related to onshore cables, as this type of cable does not usually have any armour.

All the previous modelling programs were grouped in a parent function, named *cables()*, which also takes all their inputs, selecting the correct case thanks to the values of these variables. Thus, the main function returns the requested outputs that the Matpower files require. The structure of each modelling file is explained in the following sections.

4.2.1. Functions for onshore cables and gas insulated lines

This section will be divided into two different cases, distinguishing between symmetrical flat or trefoil arrangements. The two studied onshore functions (*onshore_SC_flat.m* and *onshore_SC_trefoil.m*) have several common inputs, shown in Table 5.

It ought to be mentioned that, in order to properly study the GIL technology, the local variable named e_{CS} (i.e. relative permittivity), located in the capacitance terms calculation field, shall be changed to the corresponding value of the insulating gas (normally approximated to 1).

These programs called individually (i.e. not using the parent function *cables*) also give as outputs the RLC parameters of the π-section nominal model, as local variables. However, when the main function is called, the obtained global outputs are the same as in Table 4, which is also shown in the next page for convenience.

Variable name	Definition and units
r_1	External radius of the core conductor (r_{oc}), in mm
r_2	External radius of the first insulation layer (solid or gas, r_{is}), in mm
r_3	External radius of the sheath or enclosure (r_{os}), in mm
mat1	Material type of the core conductor, being aluminium (*mat1=1*), copper (*mat1*=2) or lead (*mat1*=3)
mat2	Material type of the sheath/enclosure, having the same options as in *mat1*
T_w	Working temperature of the conductor layers, in ºC
len	Total length of the line, in km

Table 5: General inputs in onshore cables.

Variable name	Definition and units
S_o	Total power generated by at the beginning of the line, in MVA
S_f	Power consumed at the end of the line, in MVA
R_{pu}	Value of the resistance parameter in the π-section model, in p.u. thanks to the equations: $R_{pu} = \frac{R_{pi}}{Z_b}$ $Z_b = \frac{V_b^2}{S_b}$
X_{pu}	Value of the inductance parameter in the π-section model, in p.u. thanks to the equation: $X_{pu} = 2\pi \cdot 50 \cdot \frac{L_{pi}}{Z_b}$
B_{pu}	Value of the capacitance parameter in the π-section model, in p.u. thanks to the equation: $B_{pu} = B_{pi} \cdot Z_b$

Table 4: Outputs of the modelling programs.

These two onshore functions only differ in the arrangement of the phases, and thus, in the following specific inputs, shown in Table 6.

Variable name	Definition and units	Modelling case
d	Half the distance between adjacent cables 2 and 3, in mm	Onshore, trefoil arrangement
h	Height of the triangle formed by the union of the cores (see Figure 12), in mm	Onshore, trefoil arrangement
dist	Distance between two adjacent cables (i.e. phases), in mm	Onshore, flat arrangement

Table 6: Specific inputs in each onshore program.

4.2.2. Functions for offshore cables

This modelling case is similar as the explained in the previous section, with the difference of the number of layers. Thus, the two Matlab programs regarding offshore cables (*offshore_SC_flat.m* and *offshore_SC_trefoil.m*) have the following common inputs, shown in Table 7 and defined in each file:

Variable name	Definition and units
r_1	External radius of the core conductor (r_{oc}), in mm
r_2	External radius of the first insulation layer (r_{is}), in mm
r_3	External radius of the sheath (r_{os}), in mm
r_4	Internal radius of the armour (r_{ia}), in mm
r_5	External radius of the armour (r_{oa}), in mm
r_6	External radius of the plastic sheath (r_{op}), in mm
mat1	Material type of the core conductor, being aluminium (*mat1=1*), copper (*mat1*=2) or lead (*mat1=3*)
mat2	Material type of the sheath/enclosure, having the same options as in *mat1*
mat3	Material type of the armour, having the same options as in *mat1*
T_w	Working temperature of the conductor layers, in ºC
len	Total length of the line, in km

Table 7: General inputs in offshore cables.

The only difference between these two programs are the inputs shown in Table 6. Thus, the distribution of the conductors change the geometry terms used in the impedance and susceptance equations, which can be found in section 3.2. These differences are appreciated in Annex D: Matlab files for the modelling of transmission lines.

4.2.3. Functions for pipe type cables

The last studied cable is the pipe type, the geometry of which can be appreciated in Figure 14. Due to the arrangement of the conductors, only the trefoil disposition is considered. The global inputs needed by this program (*PT_triangle.m*) are shown in Table 8.

As it can be seen, this sort of cable does not have any armour, as the pipe act as the traction reinforcement that this transmission system needs. Thus, pipe type cables can be modelled as onshore or offshore lines.

Variable name	Definition and units
r_1	External radius of the core conductor (r_{oc}), in mm
r_2	External radius of the first insulation layer (r_{is}), in mm
r_3	External radius of the sheath (r_{os}), in mm
q	Inner radius of the steel pipe, in mm
mat1	Material type of the core conductor, being aluminium (*mat1=1*), copper (*mat1=2*) or lead (*mat1=3*)
mat2	Material type of the sheath/enclosure, having the same options as in *mat1*
d	Half the distance between adjacent cables 2 and 3, in mm
h	Height of the triangle formed by the union of the cores (see Figure 12), in mm
len	Total length of the line, in km

Table 8: Global inputs needed by the modelling program corresponding to pipe type cables.

4.3. Summary of the modelling programs

This section aims to provide an schematic summary of the different modelling programs, showing the specific inputs each function needs. It shall be noted that the outputs they generate (i.e. the RLC parameters, in Ω) are stored as local variables, whereas the general inputs and outputs (those specified in the parent function) are stored as global variables, so they can be accesed by the Matpower software at anytime. This functioning is equal in overhead, cable and gas insulated lines (see Figures 18 and 19 from next pages).

The RLC parameters (in Ω) that each modelling program obtains have been conceived as local variables in order to easily calculate the needed inputs for the Matpower software, in case there is any change in the global parameters.

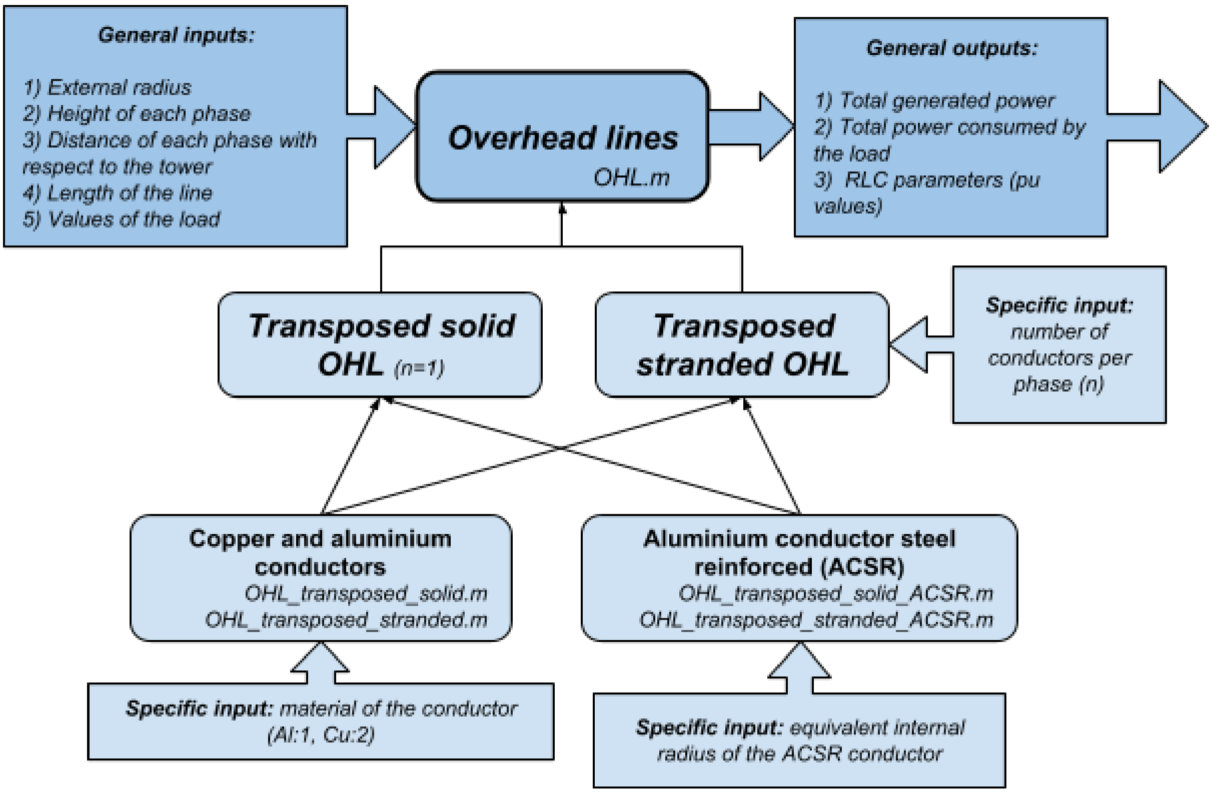

Figure 18: Schematic functioning of the OHL modelling programs.

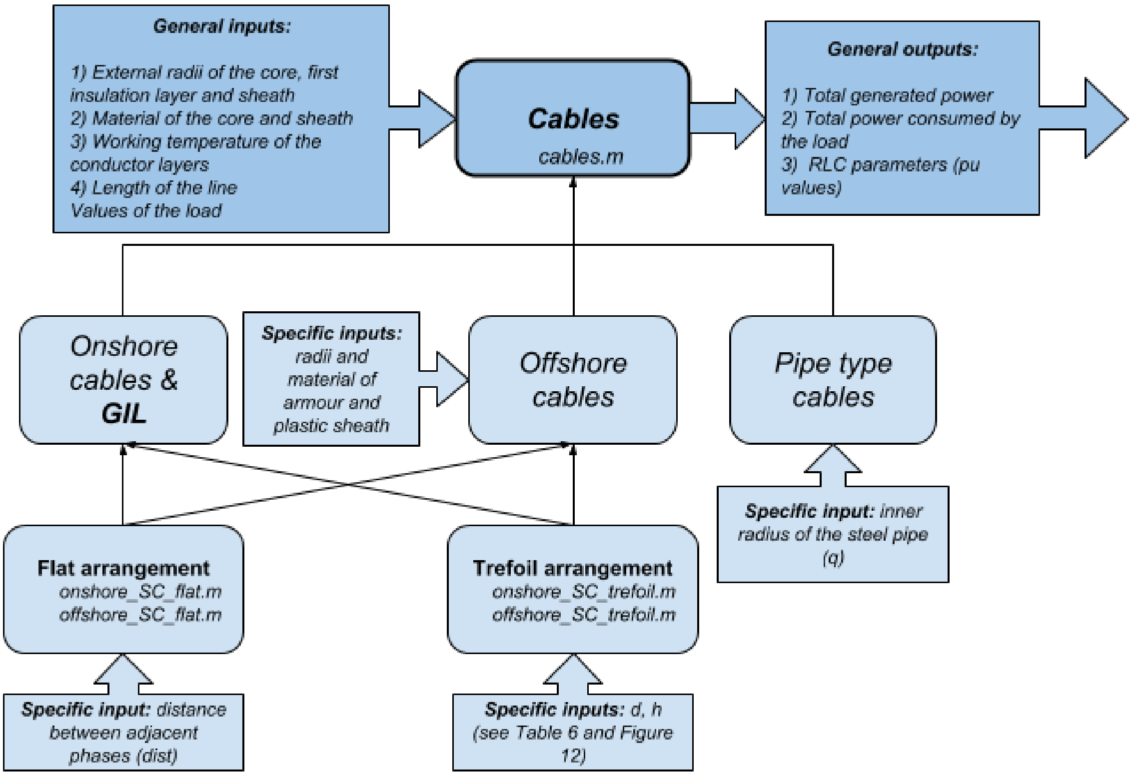

Figure 19: Schematic functioning of the cables modelling programs.

It must be mentioned that an additional script, named *global_vars.m*, has been written, in order to facilitate the use of these modelling programs. This file contains every global input that each technology needs, as well as the generated outputs, so they can be easily copied in the Matlab workspace and Matpower functions.

5. Power flow analysis

Once the RLC parameters (in p.u.) are determined, and therefore the π-section model of the line, the next logical step is to study the behaviour of the transmission system in a real situation. The aim of this chapter is consequently to show how the modelling Matlab programs were included in an already existing software specifically conceived for the determination of power flows, i.e. Matpower (version 6.0).

The Matpower tool is a Matlab programming package, initially developed by Ray D. Zimmerman, Carlos E. Murillo-Sanchez and Deqiang Gan under the direction of Robert J. Thomas. This free software was born out of the computational requirements in a real simulation project regarding transmission systems, thus requiring powerful ways of determining the normal and optimal power flows. Hence, it is a useful and complete tool used in the simulation of renewable generation systems.

In this chapter, a brief explanation of the structure of the Matpower functions is provided, as well as the introduction of the modelling variables. It must be mentioned that, as explaining in detail the entire Matpower package is not the goal of this chapter, the user is encouraged to refer to the Matpower user's manual (reference [22] of the bibliography, as well as reference [23]).

5.1. Introduction to the power flow analysis

A transmission line can be roughly seen as a group of electric buses, connected by different branches, which can be specified thanks to the RLC parameters of the π-section model. Thus, an electric bus belonging to a transmission system can be classified as one of the following:

- **PQ buses**. These buses have known active and reactive power, lacking from generation power. They are the uptake points, and correspond to loads (fixed or dispatchable[31]) or impedances. Thus, there are n_c PQ buses in a real line.

- **PV buses**. This sort of buses has known active power, consumed as well as generated, besides a determined voltage magnitude. A transmission system has n_g PV buses.

- **Slack bus**. Each transmission line has only a single bus of this type, as it sets the reference angle of the electric system, being n its index. Its active power is also known. It must be mentioned that a bus can be PV and slack at the same time.

[31] See the Matpower manual for further information.

The power flow problem is solved thanks to the Newton-Raphson method (briefly explained in Annex G), as it provides accurate results, also in huge transmission lines. Moreover, this method is used by default in the Matpower software, providing the real values of the voltages at every bus, as well as the generated, consumed and lost power. Other solving methods are plenty documented and can be easily found.

5.2. Basic functioning of the Matpower package

The Matpower software is constituted by a series of interrelated functions, each conceived to accomplish a specific function, such as setting the data (*caseX.m*, being *X* the number of buses the file contemplates), solving the power flow (*runpf.m*) and defining the indices (*idx_brch* and *idx_bus*), amongst others.

However, in this project is from special significance explaining the functioning of the *caseX.m* files, as they are programs that allow the user to define the previously modelled HVAC transmission systems, thanks to the global variables[32]. Therefore, the parameters needed by this software (i.e. values of the branches, generators and loads[33]), as well as their meaning, are explained in this section.

It is important to know that these values, in the version 2 format of the software, are introduced in a struct array (i.e. a variable that groups several data or variables in containers, named *fields*), following the IEEE CDF and PTI formats. The fields of this struct include the parameters the user needs to define before solving the power flow, being these the *baseMVA*, *bus*, *branch*, *gen* and *gencost*, this last one optional. Thus, they are all stored in the variable named *mpc* ("Matpower case"). It shall be noted that all of them are matrices, except *baseMVA*, which is a scalar.

5.2.1. Modelling of branches

In this field, the user can introduce the RLC parameters (in pu) of the obtained π-section model, as well as any transformers and phase shifters, when present. Therefore, the editable parameters in the branch *struct* are shown in Table 9, specifying the symbols used in Matpower, as well as the correspondence with the modelling functions (when present).

It shall be noted that the obtained susceptance when modelling the line corresponds to a single branch of the π-section model. Thus, it is necessary to consider the relation $b = \frac{b_{pu}}{2}$.

[32] Reference [24] of the bibliography may help the user to comprehend the functioning of this type of variables available at the Matlab software.
[33] Shunt elements can be also introduced. However, as these elements were not used in the definition of the transmission lines, they are not explained in this thesis. More information can be found in the Matpower user's manual.

Parameter name and Matlab symbol	Description and units	Matpower symbol[34]	Location
Series impedance, R_{pu} and X_{pu}	π-section model's resistance and inductance, in pu	*r, x*	*Branch* matrix, 3rd and 4th columns
Charging susceptance, B_{pu}	Total susceptance of the π-section model, in pu	*b*	*Branch* matrix, 5th column
Transformation magnitude	Relation between the number of coils of the primary and secondary circuits	τ, *ratio*	*Branch* matrix, 9th column
Transformation phase shift	Angle difference that the phase shifter, when present, applies to the secondary circuit	θ_{shift}, *angle*	*Branch* matrix, 10th column

Table 9: Branch data used in the setting at the beginning of the power flow.

Each branch is modelled in a single row of the *branch* field. Thus, the previously modelled transmission line shall correspond to a line of this *struct* matrix, specifying the buses it connects (parameters *from* and *to*, respectively). The model of a branch is shown in Figure 20:

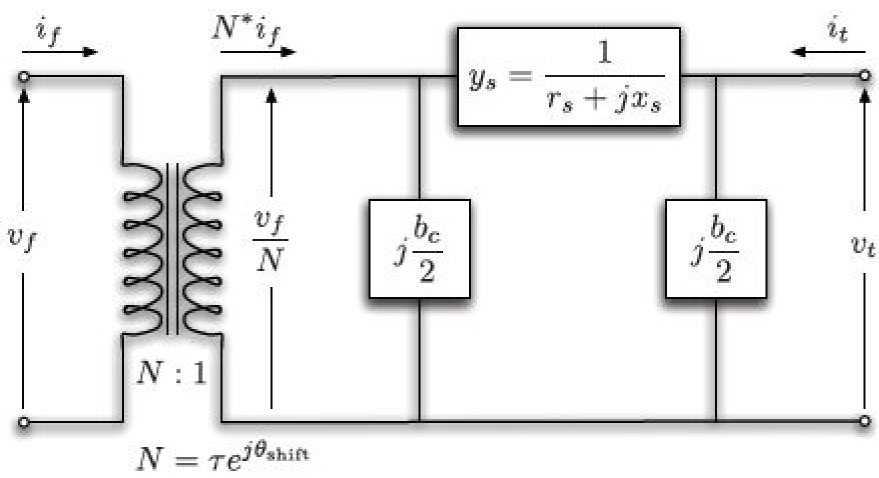

Figure 20: Branch model of the line, in pu units and studying a single phase.

As seen along this section, the modelling parameters for the branch *field* that Matpower demands are the global variables R_{pu}, L_{pu} and B_{pu}. The determination of the transformer is carried out separately, as the determination of the π-section model does not

[34] Symbols specified in each *caseX* file, when introducing the values.

require the specification of this element. Thus, the parameters of the transformers and phase shifters are introduced as values, instead of global variables. This data is normally required when one of the lines needs a reduction of the current (i.e. from MV to HV values), in order to diminish the power losses due to the Joule effect. However, it is not necessary to define them in systems with a single branch, as there are two of these elements (at the beginning and the end of the line), being the effect of the first one cancelled by the other (i.e. the current is returned to its former magnitude and angle).

It shall be mentioned that, in order to include the branch being designed into a power flow analysis, the value of *BR_STATUS* shall be switched to the value *1* (operative). Other parameters can be found in this field, such as *MU_SF*, *MU_ST*, *MU_ANGMIN* and *MU_ANGMAX*, amongst others, being these KKT constants, thus defined in optimal power flow studies. More information about these parameters can be found in the Appendix B of the Matpower user's manual (specifically Table B-3), as they are not relevant in this study.

5.2.2. Modelling of generators

In this field, the user can introduce the values of the generation bus (or PV bus), obtained from the previously determined π-section model, thanks to the transmission matrix and the definition of the load (see section 3.1.1). The total MVA base of the machine can also be included here, which is *baseMVA* by default. Therefore, the values of the generator *i* are the following:

$$s_g^i = p_g^i + jq_g^i \qquad \textbf{(87)}$$

It shall be mentioned that these modelling parameters must be included as values in MW and MVAr units: the software converts them to pu. The introduced total power of the generator is considered an initial value, and does not need to be accurate (i.e. the Newton-Raphson method finds the real value when the iteration process is concluded).

All the important editable parameters in the generator matrix are shown in Table 10, specifying the symbols used in Matpower, as well as the correspondence with the modelling functions, when present.

It is important that, in order to include the generation machine in the study of the power flow, the value of *GEN_STATUS* ought to be changed to *1* (or > 0), i.e. in service. The bus the generator belongs to must be also manually specified.

In this field, other parameters can also be found, such as *MU_PMAX*, *MU_PMIN*, *MU_QMAX* and *MU_QMIN*, amongst others, being defined in optimal power flow studies. More information about these parameters can be found in the Appendix B of the Matpower user's manual (specifically Table B-2).

Parameter name and Matlab symbol	Description and units	Matpower symbol	Location
Generated active power, $\Re\{S_o\}$	Real power output from bus *i*, in MW	P_g	*Generator* matrix, 2nd column
Generated reactive power, $\Im\{S_o\}$	Reactive power output from bus *i*, in MVAr	Q_g	*Generator* matrix, 3rd column
Base power[35]	Total MVA base of the machine, which defaults to *baseMVA* if unspecified	*mBase*	*Generator* matrix, 7th column

Table 10: Generator data used in the setting at the beginning of the power flow.

5.2.3. Modelling of loads and buses

The last important elements to be defined are the constant loads present in all the PV buses. If constant impedances or current loads need to be implemented, they can be introduced as shunt elements. It shall also be considered that dispatchable loads are described as negative generators in the Matpower package.

The values of a constant load are therefore shown below, also defined as MW and MVAr values, respectively, before the software converts them to pu parameters. The introduced properties of the load are initial, as the software finds its real values at the end of the problem.

$$s_d^i = p_d^i + jq_d^i \qquad \textbf{(88)}$$

The introduction of these elements is carried out in the bus field, being the editable parameters shown in Table 11, existing a correspondence between the Matpower and Matlab modelling variables.

The definition of the constant loads is therefore accomplished in the bus matrix, along with the other characteristics of the bus, such as its type (being *1=PQ*, *2=PV* and *3=slack*), the bus it corresponds to, as well as the voltage magnitude (in pu) and angle, amongst others (see Table B-1 of the Matpower user's manual). The study of optimal power flows also requires the introduction of Lagrange and Kuhn-Tucker parameters, not considered in this project.

---

[35] The value used for defining this parameter is that at which the line was designed (see chapter 7). However, when modelling systems with several buses, it is recommended to use a value of 100 MVA.

Parameter name and Matlab symbol	Description and units	Matpower symbol	Location
Consumed active power, P_d	Real power consumed at bus *i*, in MW	P_d	*Bus* matrix, 2nd column
Consumed reactive power, Q_d	Reactive power consumed at bus *i*, in MVAr	Q_d	*Bus* matrix, 3rd column

Table 11: Load data used in the setting at the beginning of the power flow.

Finally, some aspects regarding the modelling of the bus field shall be considered in order to properly define the power flow problem:

- In a *slack* bus (being a PV bus at the same time), the voltage is fixed, being its magnitude normally 1 pu or slightly above this value, and 0 º the angle, as it is the reference bus. However, the total generated power is unknown. Therefore, as explained before, the introduction of the global variable S_o (see Table 10) allows the system to start solving of the problem. In the bus field, this bus is noted as type 3.

- In a PQ bus, the values of the constant load are fixed (i.e. P_d and Q_d), thanks to the global variables defined for that purpose. However, the voltage is unknown at the beginning of the problem. Thus, the introduced parameters *Vm* (in pu) and *Va* (in º) are considered as initial values. In the bus field, this bus is noted as type 1.

- In a PV bus, the voltage magnitude, as well as the generated active power (P_o), is a known value, but orientative values of the reactive power (Q_o) and the voltage angle, are set as initial parameters. Although being temporary the initially defined reactive power of the generator, it is recommended to use values as exact as possible, in order to decrease the iterations of the software (i.e. the global variable Q_g found thanks to the transmission matrix). In the bus field, this bus is noted as type 2.

It shall be mentioned that a bus may act as generator and load at the same time. Thus, it can be defined at the Matpower package by introducing the consumed power in the bus field, and the electric power it generates, in the generator matrix.

In case there are doubts to be covered regarding the definition of the parameters, it may be helpful to also consult some of the example cases, included in the Matpower package, which were retreated from numerous problems found in specialised books (such is the case of the file *case4gs.m*, for example).

5.3. Example of application

In order to clarify the functioning of the Matlab modelling programs and their introduction into the Matpower package, a practical example will be introduced in this section. Being the principal aim of this thesis the integration of renewable generation, the study of an offshore wind farm will be explained below, step by step.

Thus, a transmission line with four buses is considered: one generation station (i.e. the whole wind farm acting as a PV bus), which transforms the kinetic energy of the wind into electric energy, being this also the *slack* bus, and three different loads (PQ buses). All the elements are located in the same area[36]. The structure of the transmission system can be appreciated in Figure 21:

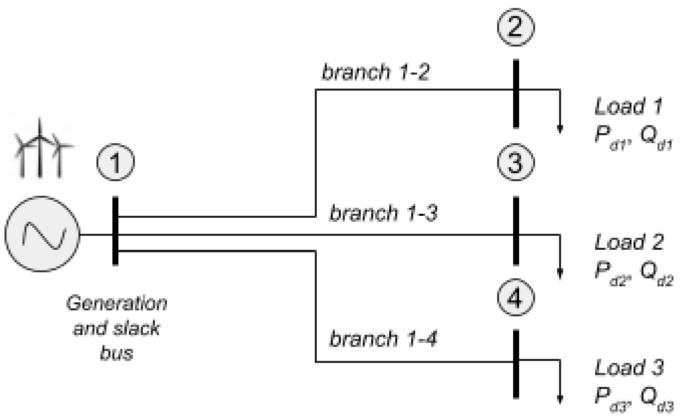

Figure 21: Structure of the studied transmission system.

All the branches can be studied as an individual π-section model, corresponding to the offshore cable technology, all of them designed at a nominal voltage of 275 kV, disposed as a flat arrangement. In this practical example, the first bus only acts a generator, without having any attached load. The voltage at which the generator works is initially unknown, as it needs to be designed thanks to the power flow analysis. However, its specifications are that this element might work between the 95% and the 107% of its capacity.

Therefore, the full study of this system (i.e. the specification of the elements in the line, as well as its modelling and power flow analysis) is explained in the sections below.

In the designing of this transmission line, no phase shifters or transformers were considered, as the line is a HVAC transmission system with similar voltages in the three branches. Hence, although existing, the transformers do not need to be introduced in the Matpower software, as the increased initial voltage is reduced to its former value before the generated power is distributed: the *ratio* and *phase* parameters can be set up to 1 and 0, respectively.

[36] This statement will allow to define the *area* parameter of the bus field afterwards.

5.3.1. Modelling of the offshore cables

In order to perform a power flow study, it is first necessary to elaborate the mathematical model of all the branches by determining the RLC parameters, by defining the geometry, arrangement and material of each offshore cable. Thus, the design values of each branch (considered of equal dimensions and materials) are shown in Table 12[37]:

External core radius (mm), r_1	21,9
External first insulation layer (mm), r_2	37,9
External sheath radius (mm), r_3	40,9
External second insulation layer radius (mm), r_4	43,9
External armour radius (mm), r_5	47
External plastic sheath radius (mm), r_6	50
Material type of the conductor (core, sheath and armour), *mat1*, *mat2* and *mat3*	Copper, lead and aluminium
Material type of the insulation layers[38]	Paper (first layer) and PVC
Working temperature (ºC), T_w[39]	75
Distance between adjacent phases (mm), *dist*	127
Length of the line (km), *len*	60

Table 12: Design values of the offshore cables.

The values of these global variables were obtained thanks to specifying the nominal voltage, current and power of the line, calculation carried out in previous Matlab programs, not implemented in this thesis (see chapter 7).

Finally, the characteristics of each load ought to be determined, as the system ought to be designed in order to fully cover the electric demand, see Table 13 in the next page.

[37] Most of them retrieved from *Power Systems Modelling and Fault Analysis*, by Nasser Tleis, chapter 3.3.7.
[38] Although not being these parameters a global input of the modelling program, they can be directly specified in the *offshore_SC_flat.m* file, being the options shown: XLPE, EPR, PVC and paper. The user can, of course, define other insulating materials.
[39] The value of the working temperature is justified thanks to the reference number [25] of the bibliography (section 2.1.2.3).

First load (bus 2)	Active power consumed by the load (MW), P_{f1}	100
	Power factor angle (rad), φ_{f1}	$\frac{\pi}{8}$
Second load (bus 3)	Active power consumed by the load (MW), P_{f2}	150
	Power factor angle (rad), φ_{f2}	$\frac{\pi}{6}$
Third load (bus 4)	Active power consumed by the load (MW), P_{f3}	200
	Power factor angle (rad), φ_{f3}	$\frac{\pi}{8}$

Table 13: Characteristics of the loads.

Before the parent function *cables* is called, it is necessary to define some parameters, as the program need them in order to select the case of study. These variables are the following: *q*, *d* and *h*, being 0 all of them, as they are parameters of pipe type cables (the first one) or the trefoil arrangement (*d* and *h*). More information of all inputs can be found inside the functions.

After all necessary variables are defined in the Matlab prompt (see Annex D, section D.2 for convenience), the user can run the main function, obtaining the RLC global parameters in per unit values. The obtained parameters for all the lines can be appreciated in Table 14, being equal in all cases (the geometry, distribution and materials are the same in all branches):

Resistance (in pu), R_{pu}	0,0025
Inductance (in pu), X_{pu}	0,0112
Susceptance (in pu), B_{pu}	0,0486

Table 14: electric parameters of the branches.

In case the offshore cables have different geometries, it is necessary to define these variables with different names, as they otherwise change their value each time the program is called (for example, *Rpu1*, *Rpu2* and *Rpu3*, having the same case with the other global outputs).

5.3.2. Introduction of the parameters into Matpower

Once the electric parameters are calculated by the Matlab modelling programs, they need to be introduced in the Matpower software, as well as the power of the loads and the base values (in this case, we use a base power of 100 MVA, due to having multiple systems). A specific *case* file was created for this practical example, following the PTI format, named as *case4.m*, which can be seen in Annex D. The parameters required by

Matpower were introduced in the file as appreciated in Figure 22. This step is necessary when including any of the modelling global variables, as these functions do not belong to the same directory as the Matpower package. However, it is advisable to introduce the parameters into matrices when studying a huge transmission system (for example, write a matrix with the consumed power by all the loads).

```
%%-----  Power Flow Data  -----%%
%% system MVA base
mpc.baseMVA = 100;

%% introduction of the obtained parameters

global So
global Sf1;
global Sf2;
global Sf3;
global Rpu;
global Xpu;
global Bpu;


%% power uptake buses, MVA
Pd1=real(Sf1); %MW
Qd1=imag(Sf1); %MVAr
Pd2=real(Sf2); %MW
Qd2=imag(Sf2); %MVAr
Pd3=real(Sf3); %MW
Qd3=imag(Sf3); %MVAr

%% initial values of the generator, MVA
Pg=real(So);
Qg=imag(So);
```

Figure 22: Introduction of the global variables required by case4 (Matpower).

Hence, the definition of the bus, generator and branch fields can be seen in the following matrices, when each column correspond to a single parameter, specifying the important inputs below them.

$$
\begin{array}{c}
mpc.bus = \left(\begin{array}{ccccccccccccc}
1 & 3 & 0 & 0 & 0 & 0 & 1 & 1,05 & 0 & 275 & 1 & 1,07 & 0,95 \\
2 & 1 & Pd1 & Qd1 & 0 & 0 & 1 & 1 & 0 & 275 & 1 & 1,07 & 0,95 \\
3 & 1 & Pd2 & Qd2 & 0 & 0 & 1 & 1 & 0 & 275 & 1 & 1,07 & 0,95 \\
4 & 1 & Pd3 & Qd3 & 0 & 0 & 1 & 1 & 0 & 275 & 1 & 1,07 & 0,95
\end{array} \right) \\
\begin{array}{ccccccccccccc}
bus\_i & type & Pd & Qd & Gs & Bs & area & Vm & Va & baseKV & zone & Vmax & Vmin
\end{array}
\end{array}
$$

(89)

It can be seen that the G_s and B_s parameters are zero, due to the lack of shunt elements in the line, as there is no need for compensation of the reactive power in none of the loads (i.e. the Q_d values were taken as acceptable). Moreover, the values of V_m and V_a are one and zero for convenience (except the reference angle from the *slack* bus), as they are initial: solving the power flow will provide the real voltages (see section 5.2.3).

$$\begin{array}{l}
mpc.gen \\
= (1 \quad Pg \quad Qg \quad 100 \quad -100 \quad 1{,}07 \quad 100 \quad 1 \quad Pg1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0) \\
\quad bus \quad Pg \quad Qg \quad Qmax \quad Qmin \quad Vg \quad mBase \quad status \quad Pmax \quad Pmin
\end{array}$$

(90)

The values of the Q_{max} and Q_{min} parameters are the introduced in matrix (90) due to the design specification that the generator should operate between these values (-100 and 100 MVAr, respectively). The status input has been specified as 1, as this element is operative at the moment of analysis.

$$\begin{array}{l}
mpc.branch = \begin{pmatrix} 1 & 2 & Rpu & Xpu & 2\cdot Bpu & 100 & 100 & 100 & 1 & 0 & 1 & -360 & 360 \\ 1 & 3 & Rpu & Xpu & 2\cdot Bpu & 100 & 100 & 100 & 1 & 0 & 1 & -360 & 360 \\ 1 & 4 & Rpu & Xpu & 2\cdot Bpu & 100 & 100 & 100 & 1 & 0 & 1 & -360 & 360 \end{pmatrix} \\
\qquad\qquad fbus \quad tbus \quad r \quad x \quad b \quad rateA \quad rateB \quad rateC \quad ratio \quad angle \quad status \quad angmin \quad angmax
\end{array}$$

(91)

In this matrix, the introduction of the electric parameters can be appreciated. The values of *rateA*, *rateB* and *rateC* are 100 MVA by default (long and short term and emergency ratings, respectively). However, the user may change their value (set to 0 for unlimited ratings). As there are no restrictions in the angle difference, the *angmin* and *angmax* parameters were set to -360º and 360º, respectively.

5.3.3. Results of the power flow

After writing all the parameters in each field, the results of the power flow can be obtained thanks to calling the function *runpf(case4)* in the Matlab prompt, which are shown below. The first data set is the summary that defines the transmission system, whether the second and third ones correspond to the detailed results of the power flow: the values of the generated, consumed and lost power (due to Joule effect, as the skin and braided phenomenons have already been taken into consideration whilst the branches were modelled), as well as the voltages (in magnitude and angle) for each bus and branch were found.

```
MATPOWER Version 6.0, 16-Dec-2016 -- AC Power Flow (Newton)

Newton's method power flow converged in 4 iterations.

Converged in 0.32 seconds
================================================================================
|     System Summary                                                           |
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses              4     Total Gen Capacity     220.0         -100.0 to 100.0
Generators         1     On-line Capacity       220.0         -100.0 to 100.0
Committed Gens     1     Generation (actual)    451.9              186.4
Loads              3     Load                   450.0              210.9
  Fixed            3       Fixed                450.0              210.9
  Dispatchable     0       Dispatchable          -0.0 of -0.0       -0.0
Shunts             0     Shunt (inj)             -0.0                0.0
Branches           3     Losses (I^2 * Z)         1.93               8.64
Transformers       3     Branch Charging (inj)     -                33.1
Inter-ties         0     Total Inter-tie Flow     0.0                0.0
Areas              1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   1.057 p.u. @ bus 4          1.070 p.u. @ bus 1
Voltage Angle      -1.04 deg   @ bus 4          0.00 deg   @ bus 1
P Losses (I^2*R)             -                  1.03 MW    @ line 1-4
Q Losses (I^2*X)             -                  4.61 MVAr  @ line 1-4
```

Figure 23: Summary data of the designed transmission system.

```
================================================================================
|     Bus Data                                                                 |
================================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.070    0.000*   451.93    186.45       -         -
    2  1.064   -0.519       -         -      100.00     41.42
    3  1.058   -0.748       -         -      150.00     86.60
    4  1.057   -1.037       -         -      200.00     82.84
                        --------  --------  --------  --------
               Total:    451.93    186.45    450.00    210.87
```

Figure 24: Voltages and power related to each bus of the designed transmission line.

```
================================================================================
|     Branch Data                                                              |
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
  1      1      2    100.25     31.47   -100.00    -41.42     0.249      1.12
  2      1      3    150.65     78.51   -150.00    -86.60     0.650      2.91
  3      1      4    201.03     76.46   -200.00    -82.84     1.029      4.61
                                                            --------  --------
                                                   Total:     1.929      8.64
```

Figure 25: Branch data regarding the designed transmission system.

As seen in Figure 23, the power flow was solved using the Newton-Raphson method, as it operates well with small systems (the problem was solved in four iterations, with a total amount of time of 0,32 seconds). Hence, if the material and geometric characteristics of each branch are known (due to the specification of the electric nominal values), the designing of the transmission line can be easily achieved, thank to the introduction of the Matlab modelling functions into the powerful Matpower software.

5.3.4. Summary of the followed steps

This section aims to briefly expose the steps followed along the modelling and study of the transmission line, with the purpose of making the use of these tools more accessible to the user, being these the following:

- Being at the folder where the modelling programs are located, set all the global inputs at the Matlab prompt, with the help of the command *global* and assign the desired values to each variable.

- Before running the parent function in the command window, it is also necessary to define the global outputs, as they are necessary for the power flow analysis.

- Call the main program afterwards (i.e. *[Rpi,Lpi,Cpi]=ohl()* or *[Rpi,Lpi,Cpi]=cables()*). The *Rpi*, *Lpi* and *Cpi* are stored as local variables in the workspace belonging to these functions and cannot be used in the Matpower package, whereas the global outputs (i.e. S_o, S_f, R_{pu}, X_{pu} and B_{pu}) can.

- Check the values of the variables in searching for any error, before defining the fields of the *caseX* Matpower file. Then, the global outputs can be introduced in the function, as shown in Figure 22, following the indications explained in this chapter and in the Matpower user's manual. It shall be mentioned that there ought to be only one tabulation between each input in the matrices, with the purpose of avoiding any error.

- After defining all the settings, write *runpf(caseX)* in the Matlab prompt, while being at the Matpower folder. This final step will provide the results of the power flow.

6. Planning, economical analysis and environmental impact

6.1. Planning

This project consists on 4 main tasks that allowed the achievement of the principal objectives of the thesis. The total amount of time employed until the end of the project was approximately of 30 weeks, from the 13th February to the 10th September of 2018. In order to successfully conclude this study, each task was assigned several weeks or days to be finished, being these the following (in chronological order):

- _Study of basic concepts_ (Task 1). Reading and comprehension of the fundamental concepts of electric renewable energy transmission, such as the structure of the grid, geometry of the parts involved, steady state mathematical models and power flow methods.
- _Modelling of different types of transmission systems_ (Task 2). Comprehension of the mathematical equations involved in each technology, stating the relative hypothesis and programming each case afterwards.
- _Inclusion of the modelling programs to the Matpower software_ (Task 3). Reading and comprehension of the software's structure and functionality, with the further adjustments in the created Matlab models in order to include them into this program.
- _Conception of the memory_ (Task 4). Conception and redaction of the present document, including a detailed explanation of each task and its related concepts.

However, it shall be noted that some of these tasks have recursive behaviour, such as the elaboration and checking of the Matlab programs. This fact was taken into consideration whilst doing the planification of the project.

Figure 26 shows the Gantt diagram of all the tasks shown in Table 15 in the next page (it shall be noted that the main tasks have been divided into subtasks), which includes the execution of the previously mentioned tasks and, in Figure 27, the amount of time (in percentage) used in the realization of each task can be appreciated. It shall be noted that not all the weeks were dedicated to the elaboration of the project, as there were exceptional events such as exams.

Task 1	Research of the available transmission technologies
Task 2	Reading about the power system, its structure and materials
Task 3	Research and reading about the mathematical models
Task 4	Modelling of overhead lines
Task 5	Modelling of cables
Task 6	Modelling of gas insulated lines
Task 7	Checking and validation of the models
Task 8	Research and reading about Matpower
Task 9	Introduction of the models into Matpower
Task 10	Writing of the thesis and annexes

Table 15: Scheduled tasks during the project's duration.

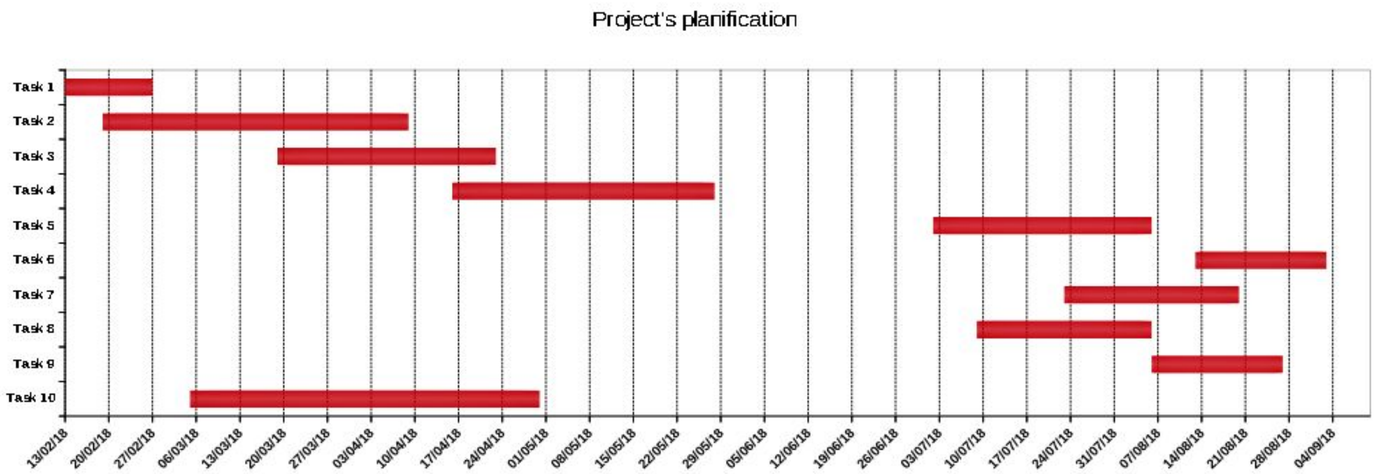

Figure 26: Gantt diagram where the different tasks fulfilled along the project can be observed.

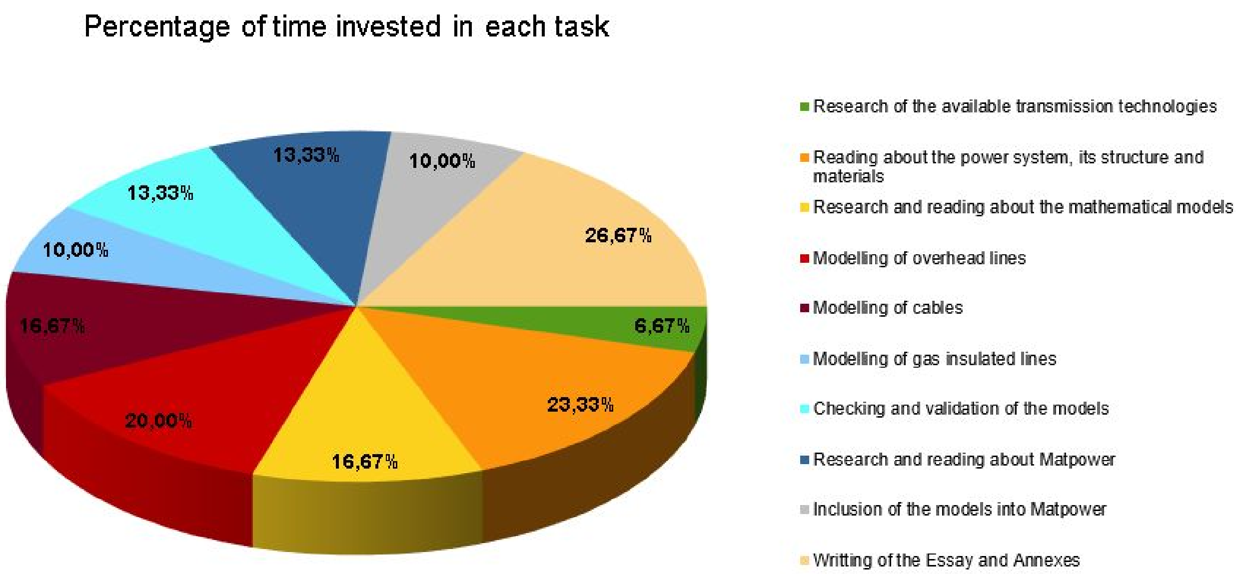

Figure 27: Diagram with the percentage of time invested on each task.

6.2. Economical analysis

After taking into consideration the amount of time invested in each task, it is necessary to calculate the cost of the project. According to ETSEIB normatives, the dedication to this project should be of approximately 360 hours.

The project started on 13th February of 2018 and was finished the 10 September of 2018. A total of 209 days conform the period of execution of the project, in these period, free days came up to be 58 days, with a mean of 3 hours of work per day. Hence, the total amount of time dedicated to the project is 453 hours.

According to reference [26] of the bibliography, where salarial tables of 2018 are presented, the pay for a bachelor's degree is stipulated to be about 6,3 €/hour. Then, the total cost of the project including the transport taxes is:

Concept:

Hours worked………..6,3 €/hour……………...x….………… 453 hours...………………..2853,9 €
Transport……………...105 €/Tjove..…………...x……………......3 Tjove....…………….……..315 €

Total…………........………..3168,9 €

6.3. Environmental impact

The present work did not have any direct environmental impact along its execution. However, some considerations shall be made, which are explained below:

- The simulations do not represent any direct impact to the environment, unless considering the source of the energy needed by the computer.

- No printed documents were used to study the subjects of the present work, neither was this thesis printed. However, many papers were used in order to write helpful and summary notes.

- No experiments that can represent any harmful impact to the environment were done.

7. Limitations and further study

As the present project was completed in a relatively short period of time, it has its limitations. Thus, this chapter intends to highlight these constraints, in order to encourage other engineers to continue with the investigation. This possible progress could include the following:

- Modelling of the transmission systems with input data such as the nominal current, power and voltage, which can be found in diverse regulations and normatives. Thus, thanks to these values, the geometry of the conductors can be obtained with the definition of a new set of Matlab functions.

- Study and further inclusion of the effect of the ground, especially in the gas insulated technology. This element has been roughly modelled. Thus, more investigation in this field ought to be considered.

- Modelling of the DC technologies, such as HVDC cables and overhead lines. Furthermore, other cases in the studied transmission systems could have been included, for example double circuits in OHL, cables and gas insulated lines.

- A new set of Matlab functions could have been implemented, regarding the study of the transmission technologies in transient state.

- The modelling programs could have been checked thanks to the PSCAD software, besides the examples found in the related documentation.

8. Conclusions

The accomplishment of the main objectives of this thesis has been a real challenge due to the level of specialization of the subject of study. Although overhead lines has been relatively easy to model, as they have been the traditional technology for the transmission of power, this has not been the case for cables and gas insulated lines, where the information was harder to find. Moreover, the designing of the modelling functions have been restricted due to the very structure of the Matpower package. However, the advantages deriving from their inclusion are more numerous than the possible drawbacks.

One of the initial objectives of this thesis was to model any transmission technology thanks to the specification of the nominal voltage, current and power at which the line is specified by normatives. However, as seen along the project, and more specifically in the previous chapter, this target was not accomplished due to time deadlines.

On one hand, a wide range of modelling possibilities has been covered with the presented Matlab functions, being an easy and clear tool to work with. However, as stated in the previous chapter, more transmission technologies ought to be included in this package in the future, in order to build a more complete modelling resource.

On the other hand, the accuracy of these Matlab functions could have been improved with the inclusion of models that would allow a more realistic study of the effect of the soil on the transmission lines. Another optimization could be the improvement of the introduction of the variables in the Matpower software, avoiding the use of global parameters.

In conclusion, despite having the previously mentioned limitations, the Matlab programs conceived for the purpose of modelling the transmission lines facilitate the engineer's task, in terms of the design of these elements. In addition, this tool is perfectly adapted to the Matpower software, allowing a complete study of the system (including the optimal power flow analysis) in a few seconds, thanks to the calculation potential that Matlab offers.

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